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Master Thesis

Weight estimation of parametrically design of fuel and hydraulic systems of a commercial airplane

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Abstract

This project aims to study the feasibility of a program capable of modelling and obtaining the total weight of the fuel system of commercial aircrafts. Once this program has been created, focus can be turned to the hydraulic system, with the aim of achieving the same.

In order to achieve this, all the components of both systems are explained, and how these components work side by side to perform the necessary functions.

A study of the current solutions used has been carried out in order to estimate the mass of the systems studied (statistical based formulas).

The methodology followed within the project is then explained in order to obtain the code: the common characteristics, patterns, calculations of the necessary elements and explanation of the hypotheses and simplifications considered.

Next, how the program works is explained in detail, carried out in Python language, the outputs that are obtained with its execution, and the limitations of the code. It is clear to see there is not enough information, or it is confidential, to make a program for the hydraulic system.

After testing the code for the fuel system, analysing the results obtained by the program and comparing them with the values of the current statistical formulas, the study concludes that although the approach of a parametric program is interesting from the point of view of flexibility, we must continue working on and improving the project, as well as collecting real data, to obtain results that point to the real value of the aircraft.

It is hoped that this project will also serve the reader as a guide to understand how both systems work and their basic functionalities.

Acknowledgments

First and foremost, I would like to thank my supervisor, Dr. Errikos Levis, for offering me the opportunity to work on this project. In addition, I would like to thank him for his help, guidance and advice as the project has developed, but above all for the kindness he has shown towards me.

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Introduction

Increasing technological improvements over the years have resulted in more tools available for the design, manufacture and validation in the engineering world. This project has a place within the first phase. Whilst not so many years ago only simple equations or empirical formulations were available for the first sketches of a design, now infinite tools are available for a better and faster design of products and machines.

The idea behind the project therefore is a way to transform these simple formulas (used to obtain in this case the weight of an airplane system) into a program that provides greater flexibility and provides extra and personalised complexity to the value of this output (the weight of the system). Although logically the designed program is far from the very powerful programs currently used in the industry, the main objective is to transform the current empirical-statistical approach of estimating the weights of these systems, into a new analytical-systemic approach.

In addition, the driving motivation behind this project, under the supervision of Dr. Errikos Levis, is to combine the benefits found by this and other similar projects under the same global code that allows a basic definition of a complete aircraft and its subsystems. Furthermore, the aim is that in the future, comparisons can be made between the current solutions for the various subsystems (fuel, hydraulic, pneumatic, and electric) and their fully electric equivalents, as the industry tends to opt for electrical technology over conventional systems. The aviation sector is certainly no exception.

Aims and Objectives

The primary aim of this project is to successfully develop a parametric program capable of estimating the number of components and their size, of the fuel system of a conventional commercial aircraft. Following on from here the intention is to try to apply the same procedure to the hydraulic system. Using these programs, the weight of the system can be obtained.

The objective is to provide a preliminary tool for the design stage so that given the basic shape of the airplane and some performance input the tool will provide precise characteristics of the aircraft. As long as the program is completely parametric, changing any variable will modify the output and the designer will be able to experiment with some grade of flexibility.

In addition, the program will show in figures the actual layout of both systems, which would give the user an initial visual idea of the interior of the airplane. These pictures are also parametric (depending on the inputs) and can vary substantially according to the chosen configuration.

The tool is more focused for derivative and change-based aircrafts due to the fact that actual data and experimental relations have been used within the code. It could be useful also for an initial idea for new aircraft, but always bearing in mind that an entire functional analysis of each part and subsystem will be vital for the success of the project.

Finally, another objective once the program is finished will be validate the reliability of the program by comparing the weight results with known data, and with results obtained by methods recognized by the industry.

All the code has been written in Python 2.7 libraries.

Fuel System

All powered airplanes require fuel on board to operate their engines. The next two subchapters will explain, first, the main components that the fuel system contains and, then, how these are arranged and connected to develop all the functions and requirements needed. The objective of this chapter is to explain to the reader who is not familiarised with fuel systems so he can understand clearly the rest of the document. The information will be complemented by some necessary images. This way, the methodology section will be clear, with no need of clarifying concepts. However, it will not be explained the innerworkings of the internal components as they are considered outside of the scope of this project. If the comprehension of the functioning for any component was needed for the developing of the code, it will be mentioned in the Methodology section.

Components

All the aircrafts share the same components in the fuel system, only varying in the quantity or the arrangement. In this section, these elements will be explained along with the main purpose to use each one:

Fuel tanks

Their mission is to store the fuel that will fed to the engines without any leakage. A fuel tank can be rigid, removable, bladder or integral. This project only considers the last ones as they are the solution used in all commercial airplanes. An integral tank forms a tank as a unit within the airframe structure, then we have the highest volume of space available with the lowest weight. This solution is also called wet wings. Therefore, the tanks can be classified according to their position in the structure (see Figure 1):

- Wing tanks: Are the main tanks of the airplane and they have the biggest capacity. There is a lot of space in these tanks. In addition, the fuel weight in the wings is used for offsetting the shear forces and bending moments produced by the wing during the flight stage. It's important to know that the wing is normally sealed into separated tanks. With these separations we can divide the tanks between feed and transfer tanks. The first are the ones linked with the engines. Moreover, they can have a collector cell where the boost pumps (explained later) are located.
- Vent/Surge tank: Is a part of the vent system. Connected to the other tanks between the ventilation pipes, the main function of this empty tanks is equalising the air pressure (during the different stages of the flight) above the fuel in the tanks to that of the ambient pressure. The vent tanks have an orifice to the atmosphere. They are also used to contain the expansion of the fuel due to temperature changes. They are always located at the end of the wing/tail (never in the center), but some huge aircrafts, like the A380, can also have extra surge tanks in the middle of the wings.
- Center tank (optional): Some aircrafts incorporate a tank in the fuselage as part of the adjoining wing box within the section. This gives more capacity of fuel. It has to be emptied before the wing tanks.
- Rear center/auxiliary tank (optional): Not very common, it is an extra tank behind the main center tank that is used to extend the range of the aircraft even further. It usually exists in place of added payload weight.
- Trim tank (optional): Finally, the trim tank is a very common solution in many long aircrafts for the control of the centre of gravity, transferring fuel from this tank to forward tanks. It is located in a part of the horizontal stabiliser of the tail.

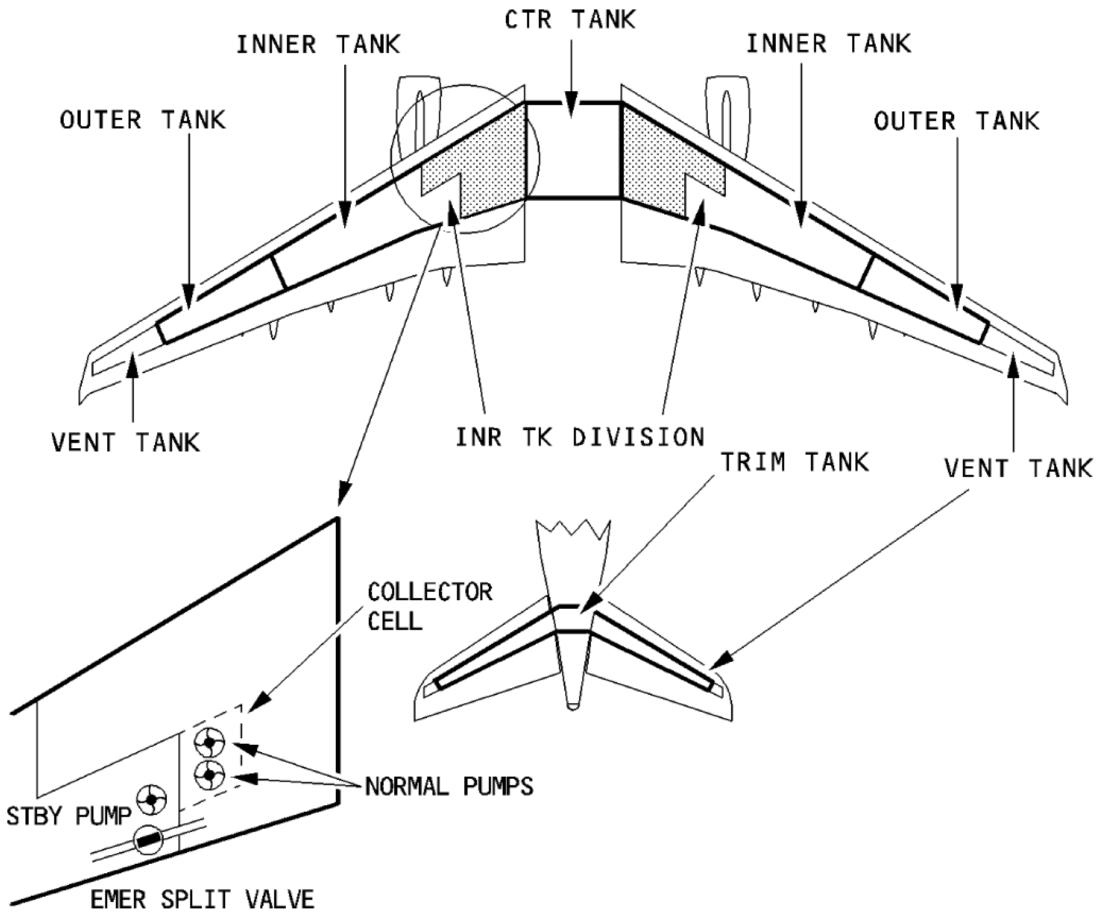

Figure 1: Tanks distribution in the Airbus A330 [1].

Fuel pumps

All commercial aircrafts use fuel pumps to feed their engines or to move fuel between the tanks. All the pumps can be categorized into different technologies but is more important to classify them into the function that they perform in the fuel system. Nevertheless, a more used technology is the gear type constant displacement and, overall, the piston type variable displacement.

- Engine driven pump (EDP): Is one of the most important elements of the fuel system. Each engine has one fuel pump to deliver clean fuel under high pressure in the exact rate to the fuel metering device. These types of pumps are mechanical and they are installed on the engine accessory gear box of the engine.
- Auxiliary/boost: Auxiliary electrical pumps are used to provide fuel under positive pressure to the engine-driven pump and during the start, when the engine-driven pump is not yet up to speed for enough fuel delivery. They are also used to back up the engine-driven pump during take-off and at high altitude to guard against vapor lock.
- Transfer pumps: These electrical pumps are used to move fuel from one tank to another at medium flow rate and pressure. Some centrifugal fuel pumps operate at more than one speed, as selected by the pilot, depending on the phase of aircraft operation. Single-speed fuel pumps are also common. Centrifugal fuel pumps, located in fuel tanks, ensure positive pressure throughout the fuel system regardless of temperature, altitude, or flight attitude thus preventing vapor lock.

- Jettison pumps: The difference between the previous electrical pumps and these ones is basically that jettison pumps can give a bigger fuel flow rate and pressure according to the requirements of this function (explained later).
- Scavenge ejector pumps: These pumps are used to remove condensed water accumulated in the fuel tanks via the vent system.

The electrical pumps can be powered by alternative or continue current. The most common is that only the APU pump is DC powered while all the others are AC powered. The APU pump is a small electrical pump that feeds the APU from one of the feed tanks.

Valves

They are many fuel valves uses in aircraft fuel systems. Large aircrafts have numerous valves. We can use them to shut off the fuel flow or to route the fuel to a desired location. Most commonly opened and closed type are known by different names related to their location and function in the fuel system: shutoff, transfer, crossfeed, isolation valves, etc. Check valves are very regular too. Besides, the system has also a lot of valves for draining (removing accumulated water from the tanks) and venting, as well as for transferring by gravity between tank compartments. Although in small aircrafts the manual (mechanical) valves are usual, all the commercial airplanes use electrical actuators for opening or closing them. These actuators are type 90º and they work with a continue current. All the valves are electronically automatized and controlled, although the pilot can change the status manually as well.

Lines/conveyance

These components form together the web with which the fuel moves around to arrive where it is needed (feeding engines, transferring, jettison). The lines are one of the parts that has improved the most these past years. The progress in material research has been achieved to substantially reduce the diameter of the fuel lines without increasing the drop losses. In addition, this makes the hoses flexible (this way they can deal with vibrations). Therefore, the linear weight of the lines is smaller than in the past. An example of a recent [2] hose is the one made of a conductive convoluted PTFE tube and a reinforcement. The fittings are fabricated with stainless steel. Sometimes they have fire protection (fire sleeve cover). Logically, different options of materials and reinforcements exist depending on the final requirements and applications.

The diameter of the hose depends on the fuel flow rate that these lines must move. Thus, it depends on what is connected one particular line.

Inside this group we can also consider the venting piping that independently connects the venting tank with all the compartments. These tubes are normally rigid.

Sealant

This component has the key function of avoiding leaking from the fuel tanks. It is applied along the geometrical lines that represent the union between the wing structure and the spars and the ribs. The main supplier of this product is PPG Aerospace [3], that offers technical data of every different type of sealant.

Fuel management

Corresponds to all the equipment necessary to manage and monitor the whole fuel environment on the aircraft (Fuel Quantity Indicating, FQI, System). Level indicators, sensors, gauges, fuel management manifolds, are examples of components that belong to this group.

Auxiliaries

The rest of the fuel system components like the integrated drive generator (IDG) heat exchanger in each engine, fuel filters, connection ports for refuelling/defueling (normally under the wings), and so on.

Fuel

Even though it is not considered an element in the fuel system, is the main protagonist for which the system works. Therefore, it has been considered appropriate to indicate the characteristics which are aimed for an optimal functioning.

Basically, there are two main fuel families: gasoline or AVGAS for the reciprocating engines, and jet fuel or kerosene for the turbine engines. As the last ones are obviously the ones used in commercial planes, the properties which are needed in jet fuel are:

- Higher viscosity with much lower volatility and higher boiling points than gasoline.
- More density.
- Less flammable (higher flash point).
- Colourless or straw.
- Use of biocides to kill the microbes that exist due to water impurity.
- 3 types: Jet A, Jet A1 (both have low volatility and low vapor pressure), Jet B (blend of kerosene and gasoline; for cold weather performance).

How it works

Each fuel system must provide an uninterrupted amount of fuel regardless of the aircraft's performance.

First of all, the general functions of the fuel system are the following:

- Stores fuel in tanks.
- Controls and monitors the correct quantity and pressure of fuel flow.
- Supplies fuel in the correct quantities to the fuel tanks during refuelling.
- Supplies fuel to the engines and the auxiliary power unit (APU).
- Crossfeed capacity to feed the engines and APU from any tank.
- Circulates fuel to cool the integrated drive generator (IDG).
- Keeps fuel in the outer wing for wing bending and flutter relief.
- Allows fuel jettison for rapid weight reduction.
- Fuel manage system: fuel transference from one tank to another → maintains the Center of Gravity within limits.
- Fuel system independence.
- Allows the venting of the fuel.

Note that not all aircrafts achieve this functions cause some of them depend on the complexity or the capacity desired by the manufacturer of each airplane.

Feeding

Regardless of the philosophy of each manufacturer in the system layout, the feeding of the engines works same way (Figure 2). Each engine has connected a high pressure EDP that supplies fuel to it (not drawn in the figure).

Downstream we have low pressure (LP) shutoff valves, located in each engine's pylon. The goal of these valves is to close the feeding of the respective engine in case of fire or failing. Continuing with the feed line path, we find the boost electrical pumps, located in the feed tanks or in collector cells inside the feed tanks. The transfer tanks can be considered as storage tanks which are used to keep the feed tanks full. Finally, the right and left sides of the fuel feed line are connected or divided by an electrical fuel crossfeed valve (X-FEED; that is controlled by two engines for redundancy [4]). This valve allows an engine or the APU to be supplied from the opposite side of the fuel line if there is a problem.

The APU works in a similar way, with the LP valve in the APU fuel supply line. With the only difference being that it does not need an EDP.

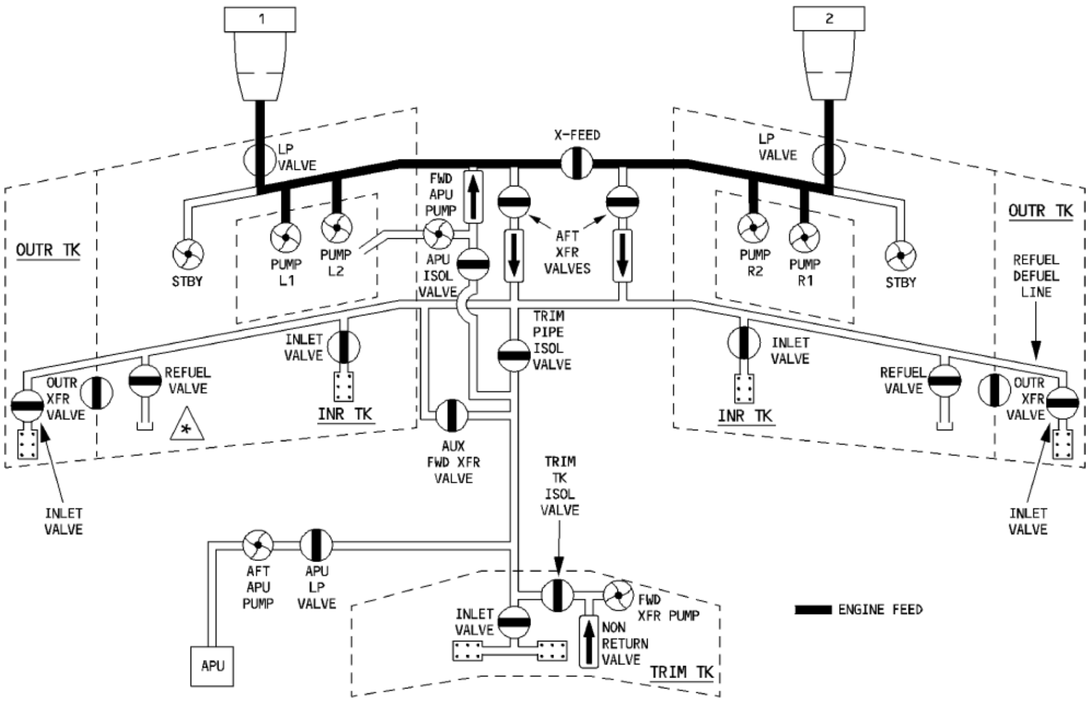

Figure 2: Fuel system layout of the A330. The feed gallery is painted in black [1].

The fuel feed sequence is automatically controlled by the system, although the manual control by the pilot is also possible. Normally, the fuel is emptied from the center of the aircraft to the tips of the wings, in the following sequence (transferring the fuel to the feed tanks):

- Center tank
- Inner tanks
- Mid tanks
- Outer tanks

Transfer

With this function is important to differentiate the aircrafts that allow transferring during flight phase from the ones that only permit transferring on ground (as a complement for refuel/defuel). In the first group, transferring during flights allows to compensate bending moments and equilibrating fuel weight. The transfer piping with all the valves and pumps is called gallery, and goes along all the spanwise of the airplane. Although the most common is to have only one gallery, some new big aircrafts like the A380 count with 2 galleries due to the increase of complexity that it has acquired. In that case, the design of the gallery system means if there is a failure in one of the galleries, the other can take over and complete the fuel transfer.

Another important function that some aircrafts must carry out is the maintaining of the optimal centre of gravity. To do that, some airplanes possess the trim tank that was explained before: as the fuel is used during flight, the balance point of the aircraft moves quite significantly. In order to keep the CofG at the optimum as long as possible, fuel is transferred out of the trim tank into the other tanks (Figure 3 shows fuel transfer when center tank is not empty, left, and when it is, right), until eventually is empty. Is important to know that even though during flights the fuel cannot be transferred from wing tanks to the trim tank.

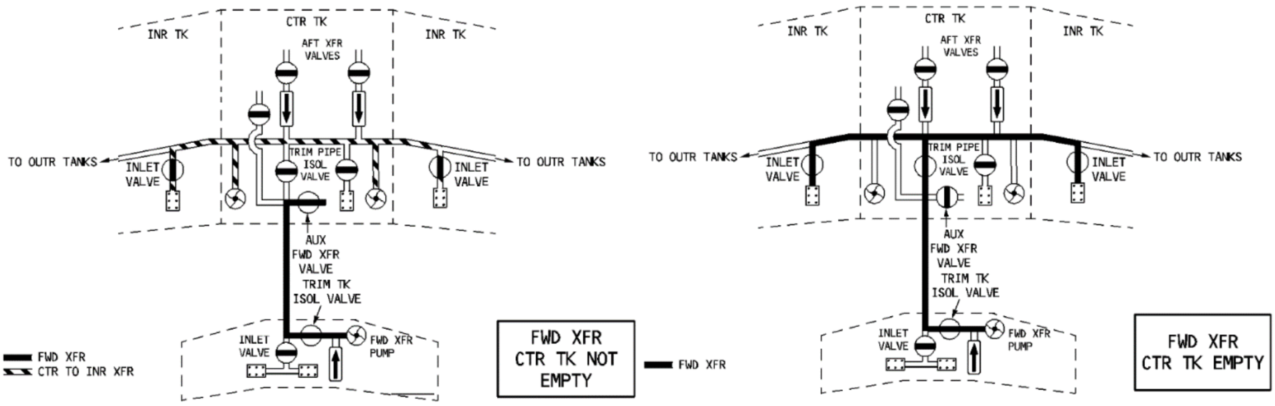

Figure 3: Forward fuel transfer in the A330 [1].

Finally, the lines used to connect the transfer galleries with the feed line (or gallery) either the trim tank in this document are called isolation lines. These lines, therefore, include isolation valves that enable them to connect the different parts.

Jettison

This optional functioning (some smaller aircrafts do not have it) consists in two nozzles (with their respective valves) at the mid or tip position of the trailing edge that dump fuel in case of emergency to reduce the aircraft's weight quickly for a safe landing.

Jettison rates can vary widely from one plane to another. Besides, the aircraft may have dedicated jettison electrical pumps or use the transfer ones (with less fuel flow rate).

Refuel/Defuel

The refuel and defuel operations are controlled by panels that are normally located under the wing or in the side of the fuselage. The main refuel hose from the airport ground is connected to the refuelling points/couplings under the wing, and all the inlet valves are conveniently opened to full the tanks. The desired fuel load is preselected on the panel and is distributed with opposite priority respect to the consumption: from outer to center. In Figure 4 can be observed how the refuelling uses the galleries explained before to full the tanks.

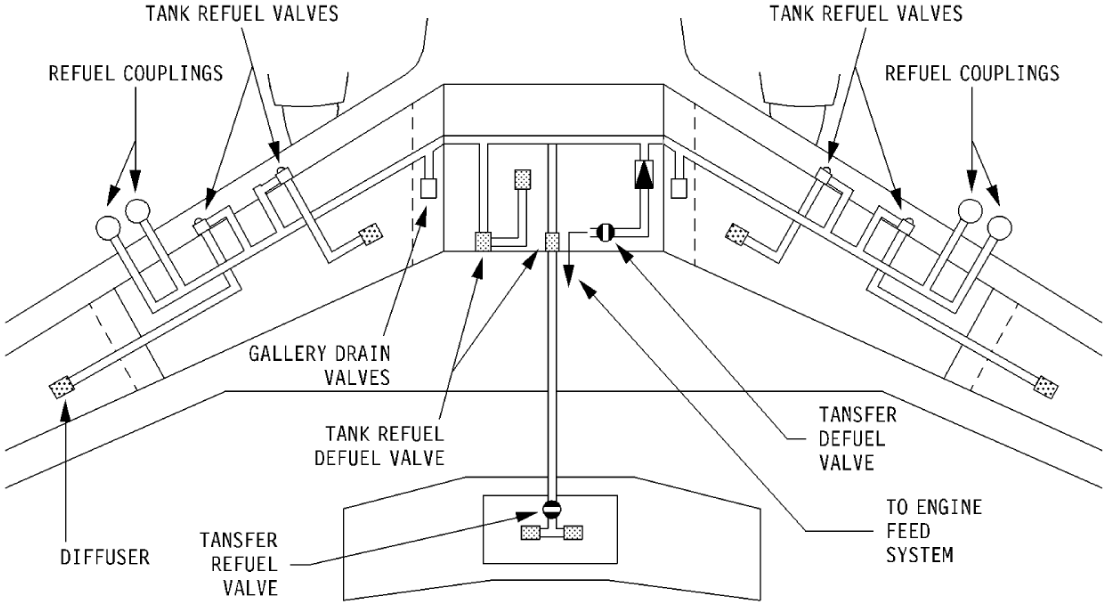

Figure 4: Refuel function in the A310. Refuelling points are under each wing [5].

Vent/Surge system

The vent tanks are located, as mentioned before, at the tip of each wing and at a part of the horizontal stabilizer. The vent system has these main functions, among others:

- Prevents the tank's overpressure during refuelling.
- Provides additional thermal expansion space for fuel from the main tanks (connected to the vent tanks by solid piping; see Figure 5).
- In flight they provide positive differential air pressure in the tanks whatever the aircraft attitude is.
- The vent tank will overflow overboard if it becomes full.

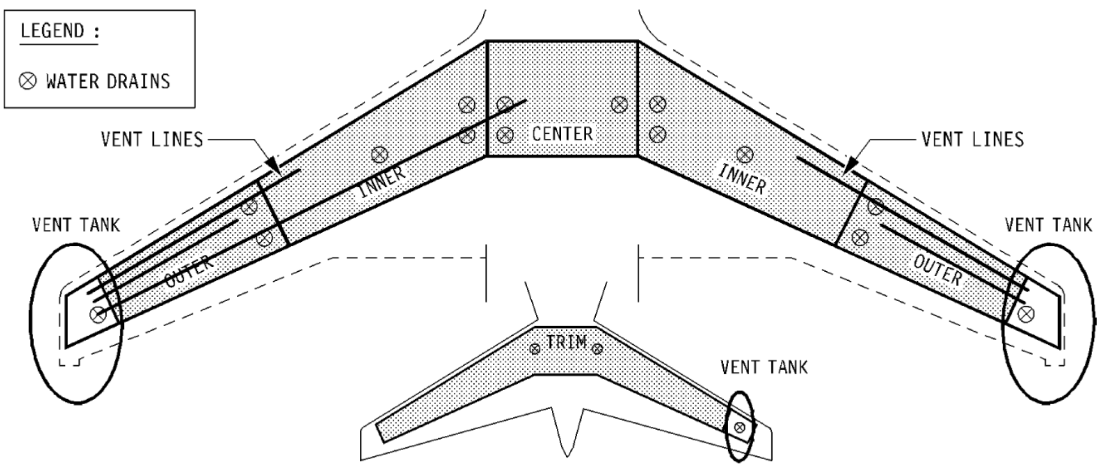

Figure 5: Venting lines connected between tanks in the A310 [5].

Fuel quantity indication and level sensing

Provides a feedback to the pilot about how is working the fuel system. The monitoring and signalling of the fuel level are out of the interest to develop this project.

Hydraulic System

Modern large aircraft make use of hydraulic power to develop functions that require elevated forces or moments. Although in the past all this was accomplished by machines or pneumatic power, when the airplanes became bigger the hydraulic power came necessary. The advantages of a hydraulic system are: light weight (important in airplanes), easy installation, and simplification of inspection and minimum maintenance requirements. Some of the main tasks that this system carries out are the following:

- To move primary flight controls: ailerons, elevator, stabilizer, rudder and spoilers.
- To move secondary flight controls: flaps, trim controls, speed brakes.
- To extend and retract the main and nose landing gears.
- To control the wheel brakes.
- To steer the landing gear.
- To operate thrust reversers.

So, as with the fuel system, the main components and how the system works will be explained as follows.

Components

In the case of the hydraulic system, the arrangement of components used from one aircraft to another is very similar. The difference between them is the quantity, which basically depends on two points: the number of functions that the hydraulic system has to do, and the redundancy required. Although as a general rule for good design in airplanes, inherent reliability is better than redundancy [6]. In this section, the main functions of each component will be explained, but the internal operation of each one is not important for this project, so is not included in this document. For further information about how they work, reference [7] can be used.

Fluid

The main difference between the fuel system and the hydraulic system is that in the second case, fluid is part of the system, since it is confined. Hydraulic liquid is used to transmit and distribute forces to various actuators. As these liquids are almost incompressible, the pressure applied to any part of a confined liquid is transmitted to every other part without loss of force. Then, the pressure can be distributed through the whole system via the fluid.

The properties needed for a good hydraulic fluid are:

- Viscosity: internal resistance to flow
- Chemical stability
- Flash point (high)
- Fire point

It's not relevant to this project neither to elaborate in more detail each property nor to examine the different types of hydraulic fluids in this document. The most famous hydraulic fluid family is the Skydrol, and further information about its types can be found online [8].

Reservoir

This is the tank where an adequate supply of fluid is stored. It supplies the fluid to the pumps and also replenishes fluid lost through leakage. Furthermore, the reservoir serves as an overflow basin for excess fluid forced out of the system by thermal expansion, the accumulators, and by piston and rod displacement. It also provides a place for the fluid to purge itself of air bubbles that may enter the system. Many reservoirs incorporate strainers in the filler neck to prevent the entry of foreign matter during servicing.

Reservoirs are either pressurized (by air or fluid) or nonpressurized. Commercial airplanes use pressurized reservoirs due to high altitude they fly.

Hydraulic pumps

The pumps are the components that give pressure to the fluid. As in the fuel system, all the pumps can be categorized into different technologies but the hydraulic system is more useful to classify by the energy source.

- Engine driven pumps: are the primary pumps in the hydraulic systems. The EDPs operate whenever the engines operate. The most widely used ones are the variable displacement piston pumps.
- Electrically driven pumps: also called ACMPs, normally operated on the ground or when there is high hydraulic system demand. They are also used for emergencies.
- Air driven pumps.
- Hand pumps: Only used in commercial airplanes as a backup unit for one or two functions.

Accumulators

The accumulator is a steel sphere divided into two chambers by a synthetic rubber diaphragm. The upper chamber contains fluid under pressure, while the lower chamber is charged with nitrogen or air. The function of an accumulator is to:

- Relieve pressure surges in the hydraulic system caused by the performance of a unit and the effort of the pump to maintain pressure at a preset level.
- Aid or supplement the power pump when several units are operating at once by supplying extra power from its accumulated or stored power.
- Store power for the limited operation of a hydraulic unit when the pump is not in use.
- Supply fluid under pressure to compensate for small internal or external (not desired) leaks that would cause the system to cycle continuously by action of the pressure switches continually kicking in.

Many aircraft have several accumulators in the hydraulic system. There may be a main system accumulator and an emergency system accumulator. There may also be auxiliary accumulators located in various sub-systems.

Lines

The same explanation as per the fuel system. The main difference between both systems is the operating pressure. Thus, the hydraulic conveyance has to be more resistant due to it works at much higher pressures.

Valves

The hydraulic system also has numerous valves to control and guide the fluid in each required part. In this system we can find more variety of valves compared to the fuel system. All the valves in commercial airplanes are electrically controlled by solenoid or servo. Following the division made by the Federal Aviation Administration [7] we can split the valves in 3 big groups. A brief explanation without entering into great complexity will be given of each type of used valve.

Flow control valves

As the name indicates, the objective is to control the speed and/or direction of fluid flow in the hydraulic system. Within this group we can find:

- Selector valve: this is used to control the direction of movement of the actuator. It controls the simultaneous flow of hydraulic fluid both into and out of the unit (the pressure and return lines).
- Check valve: it only allows the fluid to flow in one direction, and blocks it in the opposite one. Check valves can be an independent component or built in to a component. There is also a variation of these that have an orifice so the fuel in the opposite direction is restricted (but not totally blocked). They can be used as a damper and so on.
- Sequence valve: it controls the sequence of an operation between two branches in an automatic circuit. Basically, they ensure that one actuator doesn't move before a previous one has finished. They can be controlled by pressure, mechanically, or by electric switches.
- Priority valve: This important valve gives priority to the critical subsystems over the noncritical ones when the airplane has low pressure. The determination of the critical functions is within its design. Is pre-set to a pressure value. As long as the pressure is above this value, all subsystems receive pressure. When it drops below this level, the valve is closed and no fluid flows to the noncritical systems.
- Quick disconnect valves: They are basically valves for maintenance. They allow an element to be removed, for example a pump, without leakage of fluid. Another option is to connect a test between them (there are always two of these pumps, one before the element and another after).
- Hydraulic fuse: Like the electrical fuse, it closes and shuts off the fluid when the flow passing through the fuse is greater than the pre-set value. It is a safety device. The difference compared to the electrical one is that the hydraulic fuse automatically resets itself when the pressure is removed from the supply side.

Pressure control valves

The elevated pressures with which the system works require a means of controlling pressure to make a safe and efficient operation of fluid power systems.

- Relief valve: It is used to limit the amount of pressure being exerted on a confined liquid. This is necessary to prevent the failure of a component or rupture of hydraulic lines. There is a safety element that discharges fluid from the pressure line into a reservoir return line when the pressure exceeds the pre-set maximum of the valve.
- Pressure reducers: They are used not as a safety element but when a specific function requires less pressure than the normal system operating pressure. These valves provide a steady pressure. One example of application is brakes (for the pilot pedal).

Shuttle/shutoff valves

- Shuttle valves: Are used when one function (subsystem) has to be supplied from two sources: the normal system and the emergency one (that activates only essential components). In case of failure of the normal system, this valve blocks the entrance of flow from it and allows the fluid to enter from the emergency one.
- Shutoff valves: Are used to close the flow of fluid to a particular system or component.

Filters

Used to clean the hydraulic fluid, preventing foreign particles and contaminating substances to enter into the system.

The hydraulic fluid holds in suspension tiny particles of metal that are deposited during the normal wear of selector valves, pumps, and other system components. Such minute particles of metal may damage the units and parts through which they pass if they are not removed by a filter. The reliability and efficiency of the entire system depends upon adequate filtering.

Filters may be located within the reservoir, in the pressure line, in the return line, or in any other location. Modern design often uses a filter module that contains several filters and other components.

Actuators

The actuators are the last component inside the circuit. They develop the movement that the function requires. They transform fluid pressure into mechanical force which can be used to move an object (like the surface controls). One side of the actuator is attached to the fixed structure of the aircraft whilst the other is attached to the moving part. They can be single or double action type, that means that they can produce movement in one direction only or both, respectively. Commercial airplanes use the second type for faster transitions, and also because they have the ability to hold a load in position when the fluid is trapped. In airplanes we can find three types, basically:

- Linear actuators: to move control surfaces or to extend and retract the landing gear (Figure 6).
- Rotatory actuators: used for example in the nose wheel steering mechanisms. They are not limited to the 90º pivot arc typical of cylinders. Figure 7 shows how the use of a rack and a pinion gear provides large rotations in a small space.
- Hydraulic motor: is basically the same as a hydraulic pump except is used to convert hydraulic energy into mechanical (rotatory). They are used for the activation of trailing edge flaps, leading edge slats, and stabilizer trim. It's also part of the Power Transfer Unit.

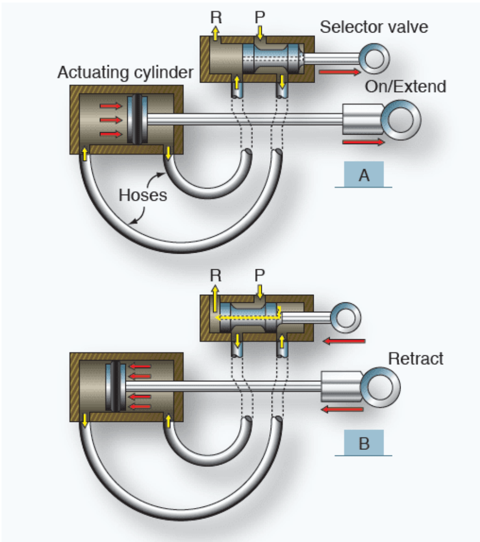

Figure 6: Linear actuator. Extension (A) and retraction (B) [7].

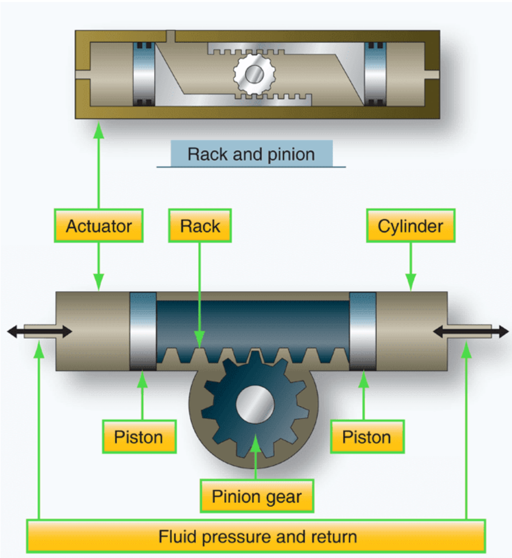

Figure 7: Rotatory actuator [7].

Power transfer unit (PTU)

This component is very important in commercial airplanes. As will be explained in the next chapter, these aircrafts count with 3 independent hydraulic systems. The PTU is an element that allows two systems to connect so in the case that one fails (loss of pressure) the other can develop the functions of the other. The PTU transfers power between them, but not fluid. We can also have PTUs that transfer power in one direction while others can do it in both.

Basically, the PTU consist of two components: a hydraulic pump and hydraulic motor connected via a single drive shaft so that power can be transferred between two systems. Notice that depending on the direction of transfer, each unit works either as a motor or a pump.

Ram air turbine (RAT)

Although it is not a component exclusively of the hydraulic system, the RAT is a backup component installed in the aircraft to provide electrical and hydraulic powers if the primary sources of power are lost. It is a turbine that can be deployed in the lower part of the aircraft and operates a hydraulic pump and generator.

How it works

The objective of this chapter is to explain how the hydraulic system works to provide fluid to the different subsystems, but does not cover how each of these functions work. They are all one or more actuators that using a simple or more complex mechanism, move components.

The easiest way to understand the hydraulic system is to explain how it works with a simple sketch. After all, the hydraulic system in an airplane is the same as this sketch, but with many more elements for security and control (already explained above under components) and with many actuators (functions)

As per the Figure 8, a basic hydraulic system consists of a reservoir, a pump, selector valve and an actuator. The reservoir supplies hydraulic fluid to the pump, which in turn raises the pressure to what the system requires (nominal pressure). Each extreme of the actuator can be connected via the selector valve to the pressure line and the return line to the reservoir. According to the position of this valve, these connections are exchanged, and the fluid moves in one direction or another. There is also the option of trapping the fluid, thereby maintaining an intermediate position of the actuator.

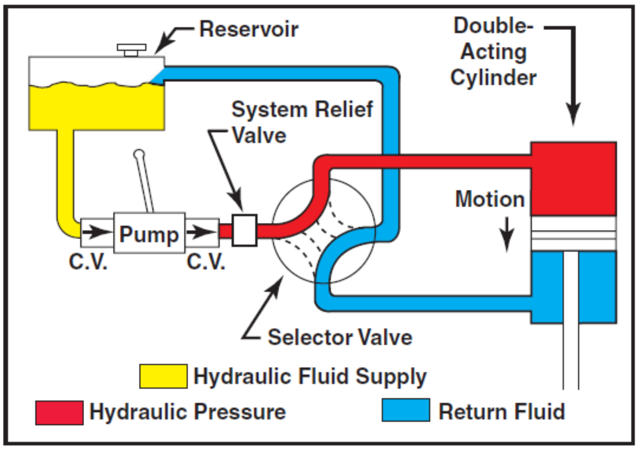

Figure 8: Simplest hydraulic circuit with coloured lines according to the function [7].

The open and closed circuits must be differentiated. Although all commercial airplanes operate with closed circuits, it is important to briefly explain the open circuits to understand the differences and why it is necessary to have second ones in aircrafts.

In an open circuit the system is not always under pressure and the components are in series. Whilst none of them are needed, the fluid circulates inside each of the selector valves and returns to the reservoir. As soon as a subsystem is needed to perform, the valve changes position and the system becomes pressurized (this takes some time). Only one component can be moved at a time.

On the other hand, a closed circuit (Figure 9) operates under pressure at all times. This is achieved through the chosen control. Without going into too much detail and considering variable displacement pumps (the most commonly used in large airplanes), an internal pump compensator automatically varies the volume of fluid required, until it reaches almost zero when the normal operating pressure of the system is reached. In this way, and for all the flow situations that are required, the nominal pressure is maintained. In addition, the components (selector valves) are connected in parallel in a way that several sub-functions can be operated at the same time. Since instant operations are required on airplanes, closed circuits are used.

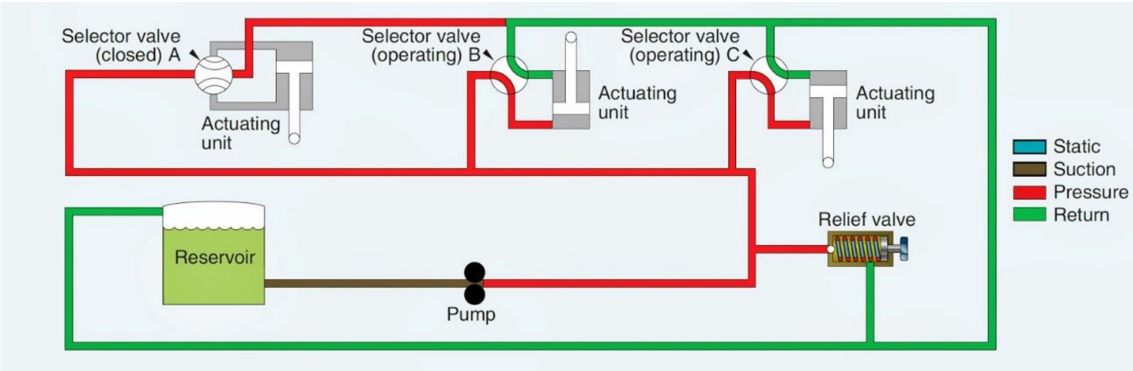

Figure 9: Hydraulic close circuit [7].
The system is continuously pressurized and actuators are arranged in parallel.

The use of this system is only limited by the volume flow capacity of the pump. The flow controls the power required by all subsystems.

Once it is understood how the basic hydraulic system works, the particularities or values with which the large commercial airplanes work can be explained.

- The current pressure of the hydraulic system is 3000 psi, and 2000 psi in the older models. The 8000 psi systems are currently being studied. These advances will allow a reduction in weight and volume of the system in the future as smaller actuators will be required. The primary objective is that all elements withstand these high pressures (greater design restrictions).
- Three totally independent hydraulic systems are used, with all the components explained in each of them, to ensure safe flight operations. Virtually all subfunctions performed are connected to at least two of the hydraulic systems. The most critical are connected to the three systems.
    - The fluid cannot be transferred from one system to another.
- The number of pumps is a compromise between the criticality of the system and the required power demand. Normally each system consists of an EDP or an electric pump, although backup units can also be used.

- All controls are currently fly-by-wire. The pilot sends the signals electronically to the servos that control the valves, without the use of mechanical links.

During normal operation (Figure 10), each hydraulic system is in charge of how its functions work. As mentioned previously, it an entire system fails, there are still two other fully functional systems that can carry out normal activity.

In case of abnormal operation, sufficient tools are available for the system's reliability, in addition to the redundancy of the systems acting on the same component. These measures can be to use the electric pumps or even deploy the RAT.

A system can also be connected through the PTU to pressurize another system that has lost the nominal pressure (damaged pump). On the other hand, if what you have is a leakage of hydraulic fluid, you must immediately disconnect the PTU and accept that this system has been lost.

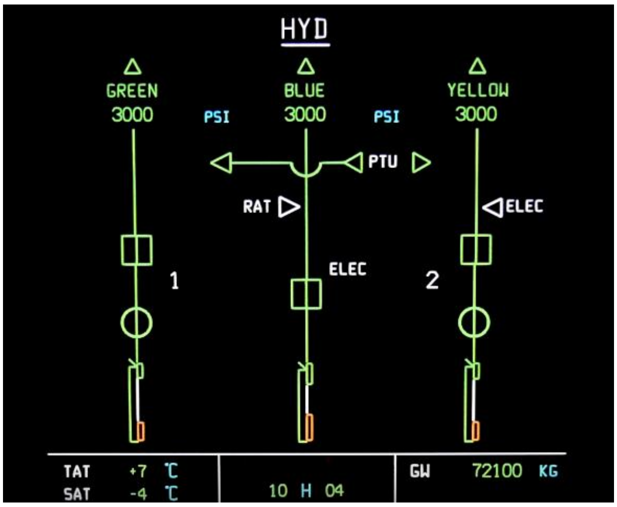

Figure 10: ECAM display for the hydraulic system during normal operation in the A320 [9].

Literature Review

Once it was understood how both systems work, and bearing in mind that one of the objectives of this project is to be able to compare the results obtained with the techniques currently used for a first estimate of these systems, it was necessary research these techniques and methodologies.

The main resources available for this purpose are based on simple formulas based on empirical regressions, statistics, or as percentages of, for example, the maximum take-off weight of the aircraft (the latter are not considered in this project since they can differ greatly from the real value). Some of these come from older books whilst others are a little more up to date. In any case, the main tools found are the following:

Raymer

In his book [10] he suggests two methods to approximate the weights of various groups within the plane. The first is a fairly rough approach based on the various structural groups of the plane. The second breaks the plane into the different functional groups and applies statistical equations based on regression analysis. For passenger or cargo aircraft:

$$W_{fuel\ system} = 2{,}405 \cdot {V_t}^{0{,}606} \cdot \frac{1}{\left(1 + \frac{V_i}{V_t}\right)} \cdot \left(1 + \frac{V_p}{V_t}\right) \cdot {N_t}^{0{,}5} \tag{1}$$

$$W_{hydraulics} = 0{,}2673 \cdot N_f \cdot (L_f + B_w)^{0{,}937} \tag{2}$$

Where:

$W_{fuel\ system}$: Weight of the fuel system (lb).

V_t: Total fuel volume (gal).

V_i: Integral tanks volume (gal).

V_p: Self sealing 'protected' tanks volume (gal).

N_t: Number of fuel tanks.

$W_{hydraulics}$: Weight of the hydraulic system (lb).

N_f: Number of functions performed by controls (typically $4 - 7$).

L_f: Total fuselage length (ft).

B_w: Wing span (ft).

Note that, in the case of commercial passenger airplanes, the formula is simplified by not having sealed protected tanks:

$$W_{fuel\ system} = 2{,}405 \cdot {V_t}^{0{,}606} \cdot \frac{1}{2} \cdot {N_t}^{0{,}5} \tag{3}$$

Torenbeek Method

In 1982 the author Egbert Torenbeek put forward various formulas to estimate the weight of the propulsion group [11]. Of these formulas, the one relating to the fuel system stands out, which according to the author is composed of:

- Fuel tanks and sealing
- Pumps, collector tanks and plumbing
- Distribution and filling system
- Fuel dump system (if used)

The equation in question for commercial aircraft with integral tanks is as follows (in metric units):

$$W_{fuel\ system} = 36{,}3 \cdot \left(N_{eng} + N_{ft} - 1\right) + 4{,}366 \cdot {N_{ft}}^{0{,}5} \cdot {V_{ft}}^{0{,}333} \tag{4}$$

Where:

$W_{fuel\ system}$: Weight of the fuel system (kg).

N_{eng}: Number of engines.

N_{ft}: Number of fuel tanks.

V_{ft}: Total fuel tank volume (liters).

The author also indicates that the number of tanks must be greater than or equal to the number of engines.

As regards the rest of the systems such as hydraulic, electric or pneumatic, in the book only a few ratios appear to obtain a very basic and not very precise approximation of the weights, so they are not of interest in this study.

NASA Estimation

NASA proposes in the study 'The Flight Optimization System Weights Estimation Method' [12] to use the following formulas to calculate the weight of the fuel and hydraulic subsystems in the case of commercial aircraft:

$$W_{fuel\ system} = 1{,}07 \cdot {W_{fuel\ cap}}^{0{,}58} \cdot {N_{eng}}^{0{,}43} \cdot {V_{max}}^{0{,}34} \tag{5}$$

$$W_{hyd} = 0{,}57 \cdot (F_{PA} + 0{,}27 \cdot W_A) \cdot \left(1 + 0{,}03 \cdot N_{eng}^{w} + 0{,}05 \cdot N_{eng}^{f}\right) \cdot \left(\frac{3000}{H_{press}}\right)^{0{,}35} \cdot (1 + 0{,}04 \cdot SWP_{var}) \cdot {V_{max}}^{0{,}33} \tag{6}$$

Where:

$W_{fuel\ system}$: Weight of the fuel system (lb).

W_{hyd}: Weight of the hydraulic system (lb).

$W_{fuel\ cap}$: Aircraft maximum fuel capacity (lb).

N_{eng}: Number of engines.

V_{max}: Maximum Mach number.

F_{PA}: Fuselage planform area (ft^2).

W_A: Reference wing area (ft^2).

N_{eng}^{w}: Number of engines on wings.

N_{eng}^{f}: Number of engines on fuselage.

H_{press}: Hydraulic system pressure (psi). The default value is 3000.

SWP_{var}: Wing variable sweep weight penalty factor ranging from 0 to 1.

These equations are two of many within NASA's own FLOPS software, and are more modern than those of Torenbeek and Raymer, in addition to being based on a more updated data set. Surprisingly, on the other hand, is the difference in variables used in the NASA methodology to estimate fuel and hydraulic systems (3 versus 7).

As it can be seen, these equations (of the three methods) only depend on a few variables and are different from one another, so the result varies widely if one of the parameters varies. This project, therefore, tries to reduce part of this variance with much more flexible inputs that really differentiate one aircraft from another.

Methodology

Once understood how the fuel and hydraulic systems work, it will be explained all the work further from the information by itself which, in a certain manner, englobes the written code. From the personalisation of the fuel system (available layouts at the moment), the detailed study for modelling each main component, to arrive to how the program actually works. Besides, this part displays all of the different considered hypothesis in their respective sections.

For a better comprehension for the reader, it has been decided to divide this section into two big blocks: the fuel system and the hydraulic system.

Fuel system

Initially, the main objective of the project was to design a program capable of modelling the fuel system of commercial aircraft.

Layouts

The essential part to carry out this project was to research as much information as possible with the aim of learning how the fuel system works inside. To do so, the key parts were the layouts or schemes of different aircrafts, the pilot manuals available in the web, and even the forums or own pilot channels of the commercial airplanes. With all of this, it was intended to detect a common construction pattern, or some basic rules for specific components, between all the available aircrafts.

The two bigger difficulties which were found in this phase were: on the one hand (and constantly during the whole project), the almost impossible chance of finding official material to explain how this systems work in detail; and on the other hand, to stablish a common logic when writing the code which will englobe the maximum amount of characteristics which are observed when the layouts between the main market companies are compared. These differences are even noticeable between Airbus and Boeing, the two big leaders of the sector.

To gather all of this information models from these companies were studied: Airbus, Boeing, McDonnell Douglas, Fokker, Embraer y Canadair-Bombardier. The more fruitful that was obtained was from the Airbus families, with a lot more official information. While, for example, the planes of the direct competition Boeing, have been studied by non-official mediums.

As the different layouts of each aircraft were observed, they were classified and the different used components were counted, with the aim of finding patterns to posteriorly writing the code. The result of part of this classification can be seen in the Appendix A.

After this introduction the different options which can be chosen in each sector of the fuel system are broken up.

Tanks

The integral fuel tanks, each one of them and their function already explained, represent a look in the space where most of the elements in the fuel system are placed. In this subsection it is only important to mention that the global complexity of the system increases if there is a bigger amount of these tanks. Is very different, for example, to have just one space (besides ventilation tank) in each wing than having some of them, adding weight but increasing the flexibility and reliability of the system.

Is important to underly that the fuel tanks do not include all the available volume of the wings. These are delimited by two structural elements, the front and the rear spar, as it necessary to leave space in the Leading Edge and the Trailing Edge for control surfaces and their mechanisms.

The number of tanks (not including the ventilation ones) right now can oscillate from 3, for example in the B727, to 11, as the A380. Both the central tank as the compensation tail tank are always unique, therefore if a plane has more tanks it is always due to the compartmentalisation of the wings.

Feeding

The fundamental part of the alimentation system is to indicate the number of engines which need to be fed and their position. This basically stablishes the complexity of the alimentation conducts. The typical locations are two: under the wings in specific percentage of the spanwise, or in the tail. Normally one or the other configuration is chosen, however, a joint solution can also happen (Figure 11).

Figure 11: McDonnell Douglas DC-10-30
with two engines under wings and a central one in tail [Source: United Airlines].

From here each engine needs a supply tank. In the case of an aircraft with an engine in the central tail, this engine feeds of two fuel tanks in the wings (which can be shared with two symmetrical engines) or from the central tank (solution adapted from the Boeing 727). Both solutions are chosen with the aim of maintaining the symmetry of the system.

Finally, the location of the supply lines depends on the predominance of the engines: if these are located under the wings, we have the conducts next to the front spar; if they are found in the tail, we have them next to the rear spar. In any case, this is just for the making of and installation and do not involve any difference in the components besides of an almost null variability in the length of the conducts. Thus, the front spar as the place of travel has been chosen arbitrarily for the program, as it represents almost all plane designs.

These explained points can be seen in Figure 12 and Figure 13. The A340 is a somewhat special plane since both engines in same wing are feed by the same tank. However, each engine has an own collector cell inside this tank. This is due that the A340 uses exactly the same layout that the A330, with two extra engines. They are also observed the valves which allow crossfeeding ("X FEED" in the Figure 12) between the engines and the feed pumps.

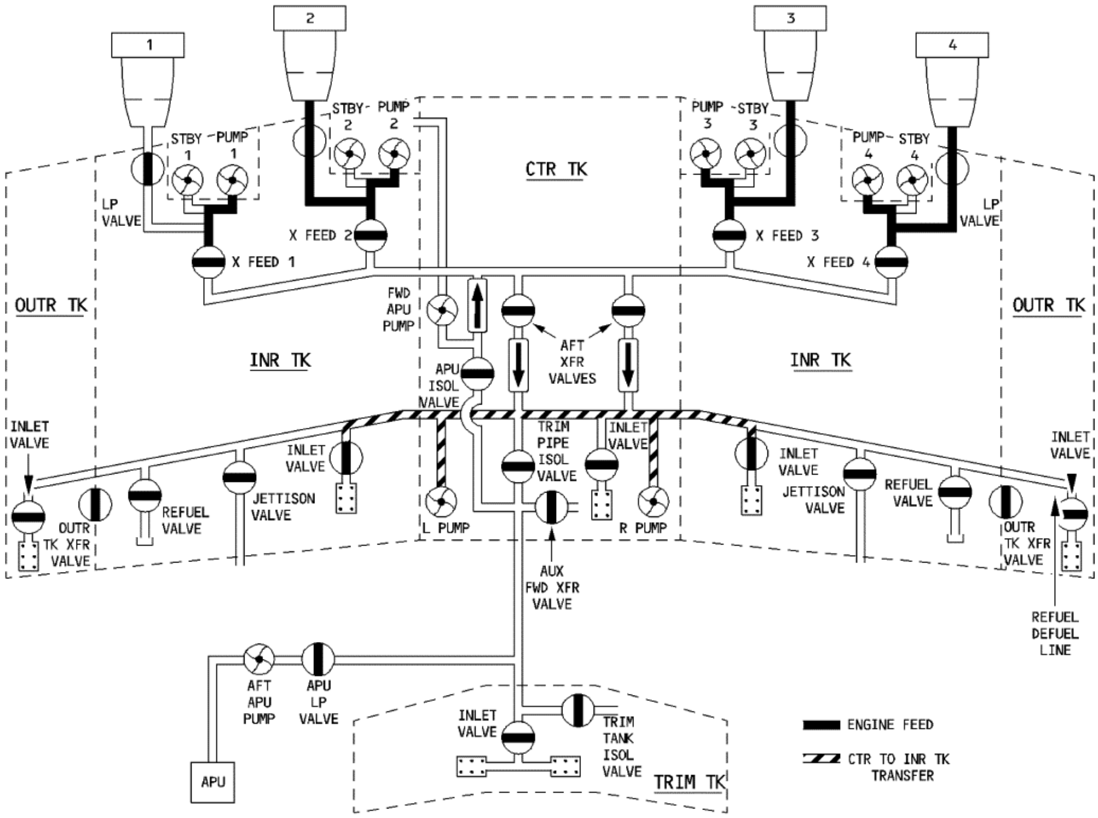

Figure 12: Airbus A340's actual fuel system layout [13].

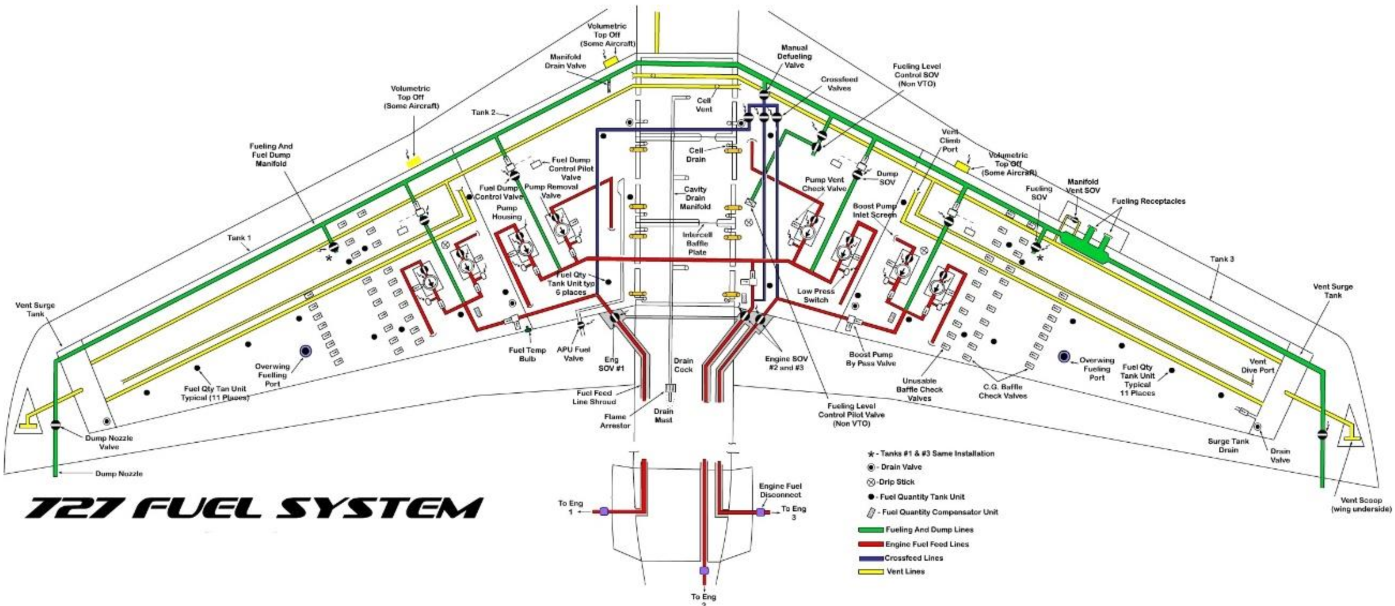

Figure 13: Boeing B727's actual fuel system layout, with three engines in tail [14].
The venting pipes can also be observed.

Transfer

The complexity of the transference system lays on basically the number of fuel tanks or the divisions it has. Its function, as its name indicates and it has been explained before, is that of moving the fuel to the required places. Even though the usual is using just one gallery, some planes with great wingspan are appearing which have two, as it is the case with the studied Airbus A380 (Figure 14).

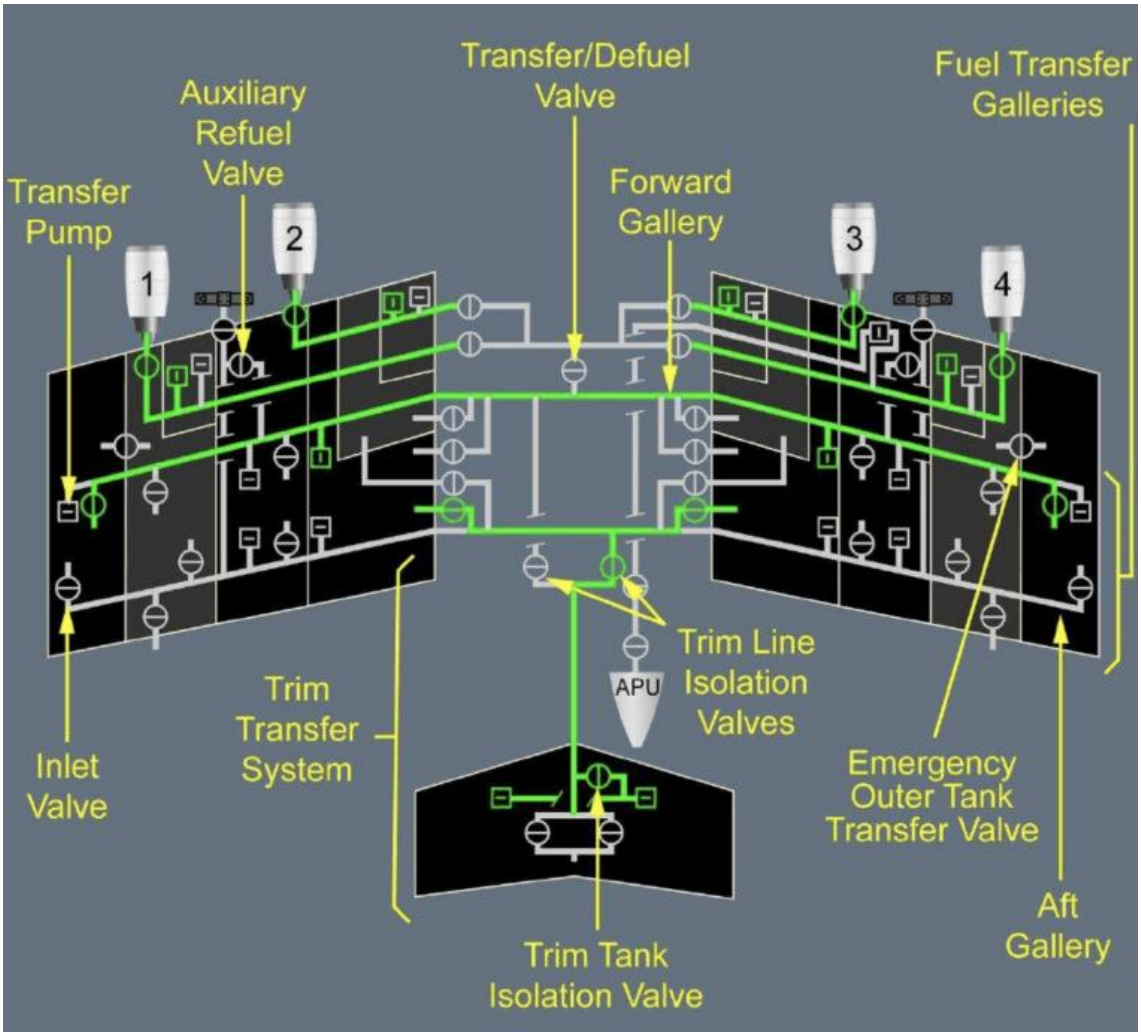

Figure 14: Airbus A380's actual fuel system layout [15].
Both galleries (aft and forward) can be observed in addition to the 11 fuel tanks that the aircraft has.

To keep explaining the elements, it is going to be used a scheme of the A380, as is more complex than the average, but useful to visualise the connexions between galleries and tanks. In the figure, valves are represented with a circle and pumps with a square. In general terms, this galleries are connected with the tanks this way: if is a transference tank, this has connected the valve and an electric pump to receive and send fuel wherever is necessary; if it is a supply tank, it has connected just one valve to the gallery to receive fuel (it does not , logically, extract fuel from the supply tanks).

In addition, the last exterior tank (outer) neither has a pump. However, at the same time is connected with its interior by a floodgate shaped valve to transfer fuel by using gravity.

This gallery is normally located on the opposite side of the feeding gallery. Therefore, generally located in the rear spar. In the case of relying on two galleries, the forward gallery is located in the medium zone.

In airplanes with trim tank in tail, this one has logically valves for the filling (as explained) and pumps to make fuel transfer and control the CofG. The number of these components depends on the aircraft size and they are connected to the transfer gallery(ies) through a pipe placed in longitudinal direction (at the center of the fuselage).

Refuel/defuel

The filling and emptying options of the fuel are achieved basically by always connecting the refuelling points (which are in themselves valves) explained before through the conducts with the transference gallery.

Isolation

The two galleries from before, the supply and the transference ones, are connected between them with valves in the middle. Therefore, in this project it was decided to name them isolation lines. These conducts are also orientated in a longitudinal direction, located between both wings of the plane. Their function is to be able to jointly use both galleries in emergency situations or, for example, for the defueling, when the boost pumps are used to guide the fuel to the transference gallery.

Jettison

If the plane has been designed to be able to use this function, two ejectors are placed in the wings (one on each side) connected to the transference gallery. These ejectors can be found in the half (solution adopted by Airbus) or in the tips (Boeing) of the wings. These ejectors can be considered like a valve.

Auxiliary Power Unit (APU)

The APU is found almost always at the end of the tail. This is like this because is an unused space in the central line, it has fire protection, and sometimes it does not need of an extra piping. Its supply is achieved, normally, by extracting fuel directly from one of the supply tanks/cells of one of the engines. A pump of a smaller size, which works with DC, extracts fuel and directs it to the APU, which has a LP valve similar to the one in the engines.

It is important to mention that two alternatives to move the fuel to the device have been observed. The first consists on an independent line just used for the APU; while the second solution, just available in the case of having a tank in the tail, uses this same line for the end. In the fist more conduct is used while in the second more valves, for the coupling and decoupling. Besides, in the case of having a compensation tank, the APU can also be fed from this one if this line is shared. The reliability is here the criteria that the designers use. In the next Figure 15 it can be seen all the options talked above:

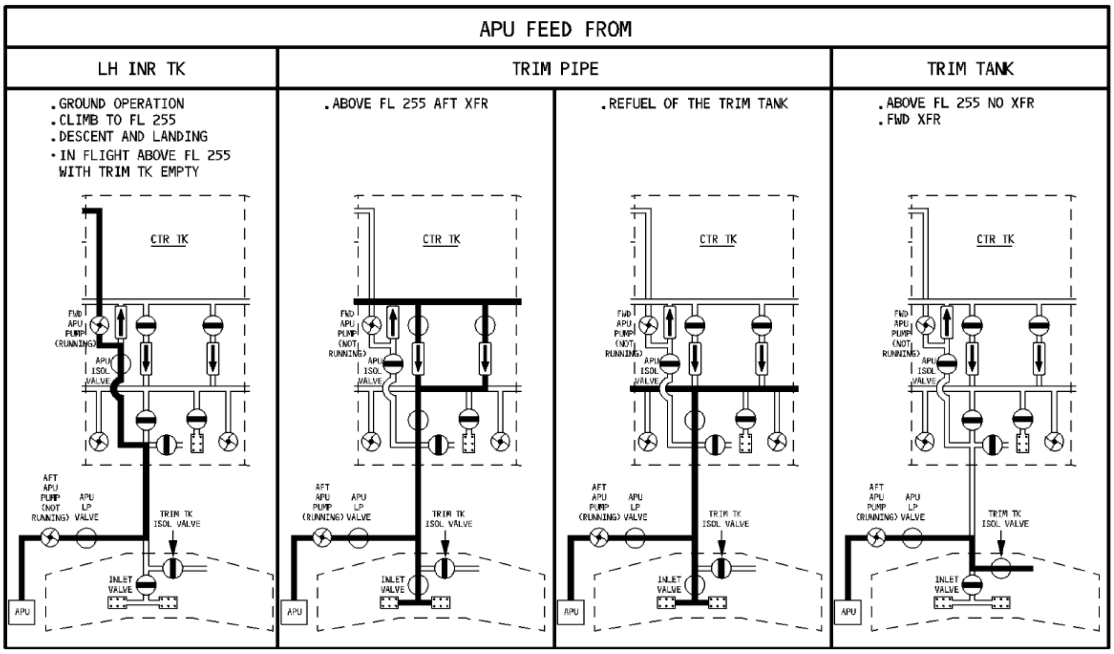

Figure 15: APU feeding in the A340 [13].
From left to right: using the collector cell and the APU pump; using the feeding line (and boost pumps); during the refuelling of the trim tank; and from the trim tank.

Weight estimation

Once the different layouts have been observed and studied, before writing the code was needed to break up in subgroups the total mass of the fuel system. This way is easier to analyse the components which can be calculated, which had to be estimated and which others could not be obtained. Thus, and in junction with how the fuel system works, the total mass of it is:

$$W_{fuel\ sys} = W_{lines} + W_{pumps} + W_{valves} + W_{sealant} + W_{fuel\ management} + W_{aux} \qquad (7)$$

Where:

$W_{fuel\ sys}$: Weight of the fuel system.

W_{lines}: Weight of the fuel piping and the vent piping.

W_{pumps}: Weight of the EDP, the electrical and the scavenge pumps.

W_{valves}: Weight of the valves (all types).

$W_{sealant}$: Weight of required sealant for the integral tanks.

$W_{fuel\ management}$: Weight of all the components for the fuel management.

$W_{auxilaries}$: Weight of all the extra components.

Hypothesis, demonstrations and calculations

In this section they are presented all the hypothesis applied to the program due to the data found and analysed in the web, the information read, or due to previous assumptions made in other researches.

In addition, on this document appear the conclusions about commercial components as valves, pumps or hoses. The information has been extracted from catalogues and manufacturers. The leader company for aerospace components is EATON [16], from where has been obtained a big part of the data.

Fuel capacity

This section contains the formulas used to calculate the maximum volume available of fuel according to the selected layout.

Equation for defining a symmetric unitary NACA airfoil [17] (upper part):

$$y_t = 5 \cdot t \cdot \left[0{,}2969 \cdot \sqrt{x} - 0{,}1260 \cdot x - 0{,}3516 \cdot x^2 + 0{,}2843 \cdot x^3 - 0{,}1015 \cdot x^4\right] \quad (8)$$

Where:

y_t: Half thickness at a given value of x, from centerline to surface (m).

x: Position along the chord $(0 \div 1)$.

t: Maximum thickness as a fraction of the chord $(0 \div 1)$.

Note that *t* gives the last two digits in the NACA 4-digit denomination divided by 100.

The length of the chord depending on the span position:

$$c(y) = \left(1 - 2 \cdot (1 - \lambda) \cdot \frac{y}{b}\right) \cdot c_r \quad (9)$$

Where:

$c(y)$: Length of the chord (m).

b: Span (m).

y: Position along the span $(0 \div b/2)$.

λ: Taper ratio

c_r: Root chord, in the centerline (m).

<u>Hypothesis</u>

- The total span of the tanks is 98% of the real span (for the tip wings).
- Wing fuel tanks are 85% usable [10] measured from the external skin surface while center tanks are idealized as cubic and are 92% usable (space for the components).
- 5% of the wing tanks is for the vent tanks [10].
- The volume in the tail tank can be calculated equal as the wings, but extending until the root (the aircraft does not have in the tail another cubic part like the center tank). Studies say [18] that thickness to chord ratio in tail is approximately 2% lower than in wings.
- In the tail (these hypotheses are supplied by the observations in the drawings of the trim tanks and by comparing the first results with the real size of the airplane's tanks):
    - Tail's rear spar = Wing's rear spar - 5%
    - The total span of the tanks is 60% of the real span approximately.

The generic volume of a tank is, then:

$$V_{i-tank} = \%_{usable} \cdot (1 - \%_{vent}) \cdot width \cdot A_{width-section} \quad (10)$$

The volume in both wings is, then (not considering the space of the center tank):

$$V_{wings} = 0{,}85 \cdot 0{,}95 \cdot 2 \cdot \int_{D/2}^{0{,}98 \cdot b/2} c(y)^2 \cdot \left(2 \cdot \int_{front\ spar}^{rear\ spar} y_t(x) \cdot dx\right) \cdot dy \tag{11}$$

The generic volume of center tank, is exists:

$$V_{center\ tank} = 0{,}92 \cdot c(D/2) \cdot (rear\ spar - front\ spar) \cdot t_{D/2} \cdot D \tag{12}$$

The volume of the trim tank in the tail, is exists:

$$V_{tail} = 0{,}85 \cdot 0{,}95 \cdot 2 \cdot \int_{0}^{0{,}6 \cdot b/2} c(y)^2 \cdot \left(2 \cdot \int_{front\ spar}^{rear\ spar - 0.05} y_t(x) \cdot dx\right) \cdot dy \tag{13}$$

Where:

b: Spanwise (m).

D: Diameter of the fuselage (m).

$c(D/2)$: Chord where wings join the fuselage (m).

$t_{D/2}$: Thickness where wings join the fuselage (m).

Layout, number of components

In this section, the patterns which have been detected by studying the different layouts/manuals of commercial planes are listed and using the information gathered from the moment the project was started. Thus, most of the conclusions in this research are personal to the writer. If they are not original conclusions, these will be properly referenced.

1. Each engine uses one, and just one, EDP. The reference [19] is the only scheme found where the pumps in the engines are drawn.
2. At the same time, each engine (or its respective EDP) is feed by two electric boost pumps which are generally located in the feed tank. In any case, it was included to the program the option of added electric boost pumps.
    a. Sometimes these pumps have mounted a sequence valve that allows feeding by gravity (case of the Airbus A320 [4]).
3. Each engine is fed by an independent fuel tank. The case of the central engine in the tail is an exception, as it is fed with two tanks (one on each wing).
4. The APU is also fed by one of the tanks talked about above (it does not have an own tank) or with a compensation tank if it is connected to it.
5. Each engine, and also the APU, count on just one Low Pressure valve to close the feeding in case of emergency.
6. For planes with 4 engines under the wing, the feeding can be independent or not; this is, each engine has their own feeding line and the crossfeed is permitted between all of them or each wing has its own line and there is just crosfeed between sides. In any way, in the layouts found, just independent feeding was seen. This implies:
    a. N crosfeed valves for N engines.

7. Regarding the fuel transference:
    a. The feeding tanks have just one entrance valve per gallery.
    b. The transference tanks have a valve and an electric pump on each gallery.
    c. If the plane has a central tank, it tends to have two electric pumps.
    d. The outer tank (the transference tank) has been seen as an exemption as it normally does not have a pump, but at the same it adds an extra valve to connect it with its adjacent and be able to transfer fuel by gravity. Sometimes, cases of smaller planes with a big transference by gravity from the extreme of the wings, do have two valves.
8. The conduits in the wings have been considered following the correct sweep angle from its respective position. The feeding gallery, generally, is found in the front spar while the transference gallery in the rear spar.
9. The refuel points are always two, one on each wing, and they are connected by valves to the number of galleries that it has.
10. If the plane possesses the jettinson function, there are always two ejectors, one on each wing. These have been modelled as another two valves.

Engine driven pumps

The whole catalogue of coupled pumps to the engine was analysed (mechanical functioning) for commercial planes and, firstly, the characteristics of the manufacturer were observed: speed (rpm), inlet pressure (psi), boost stage pressure rise (psi), discharge pressure (psi), fuel flow rate (L/min) and weight. The goal was obviously finding a relation between these variables and the weight.

The entrance pressure moves always between 15 and 30 psi, being 20 psi the most common value. Therefore, this characteristic will affect the electric pumps, as these will have to supply the fuel in this pressure to the EDP. However, it is not a parameter which has influence in the weight of the mechanical pumps.

These EDPs work so the fuel has to pass through two phases: the first is the centrifugal pump which increases the pressure to force the fuel through the internal filter to posteriorly elevate the pressure to great values in the high-pressure pump. Therefore, the packing of the whole, with the coupling shafts and the components, composes the EDP. The boost stage pressure rise, thus, is an internal parameter of the pump which represents the increase of pressure between these two phases.

Various regression studies were carried out with the variables speed, discharge pressure and fuel flow rate. What it was seen was that the two first variables do not represent a parameter of influence in the weight of the pump compared with the FFR. If a regression with two variables (FFR and discharge pressure or FFR and speed) or with three was applied, an improvement of the 5 % in the coefficient of determination R^2 was obtained.

For that reason, it was decided to include to the program the option of adding the discharge pressure (the fuel flow rate is logically the required input) to those users which know the value. Nevertheless, it is considered that with the FFR is enough and there is already a good first approximation which also offers more flexibility as it requires less inputs. The data of the study and results obtained can be seen in the Appendix B.

Electrically driven pumps

Similarly to how it was proceeded with the EDP, the diverse catalogue of electrical pumps to obtain the weight from some entrance variable was studied. The biggest difficulty with respect to the EDPs was to classify the different models depending on its main function, as the EDPs feed the engine, while these can be of type boost, jettison or of feeding of the APU.

In general terms, the electrical pumps are fed in 200 V of alternating current, excluding the alimentation of the APU, which use DC of between 18 and 29 V. Moreover, practically all of them included a canister which allow that the pump is disassembled without having to drain the tank. These supporting elements were included in the total weight of each element.

The summarised information can be read in the Appendix C and the obtained conclusions were similar to the previous for which it is not repeated here in the explanation. Basically, the final weight of the bomb is function of the flow rate, while the release pressure has practically no influence.

Valves

After analysing different types of valves along the website (Appendix D), the conclusions obtained were the following:

1. The available catalogue gives some examples of each type of valve but there is insufficient data for a clear idea about the design parameters. It made no sense, then, to try to classify the valves by pressure, flow or other variables.
2. The operation pressure of the valves is always greater than the discharge pressure of electric pumps. This means that the valves are a component designed such that they will not fail.
3. All the valves need a 90º type electric actuator to opening/closing them. The average weight of some of these actuators is included in the code for the valve's weight.

<u>Hypothesis</u>

- Same weight for the main valves (the ones drawn in the output layout) based on statistics. The variance between the available catalogue of valves is small so it's also a good reason to use an average value.
- Then, try to make an approximation of weight for the rest of the valves: check valves, draining, air, and more (function of the total length of piping and the aircraft complexity).

Engines and fuel flow rate

To size the pumps, both the mechanical as the electrical, of the fuel system it was explained that the key needed parameter is the fuel flow that has to be moved. Is obvious that the requirements of the flow of these components will be given by the maximum flow which the engines need in the moment of maximum power. The required fuel of the engine in a specific situation is:

$$FFR\left[\frac{\text{kg}}{\text{s}}\right] = SFC\left[\frac{\text{lb}}{\text{h}\cdot\text{lbf}}\right]\cdot Thrust\,[\text{lbf}]\cdot\frac{1\text{ h}}{3600\text{ s}}\cdot\frac{0{,}453592\text{ kg}}{1\text{ lb}} \qquad (14)$$

SFC (specific fuel consumption) is the mass of fuel needed to provide the net thrust for a given period. Mass of fuel is used, rather than volume for the fuel measure, since it is independent of temperature. SFC is, then, the fuel efficiency of an engine design with respect to thrust output.

The maximum value of the FFR is given in land for the take-off, as, even though the specific consumption is smaller (the engine is more efficient with higher power) the necessary thrust is much higher than in the cruise phase, were the SFC has its higher values.

With this maximum value in mind, it was tried to search methods of design to understand the fuel flows required for the pumps. Without the possibility of finding any type of useful information, the strategy was changed:

On the one hand, information was obtained, [20] and [21], of many existing commercial reaction engines, and the maximum FFR was calculated based on the previous equation. On the other hand, a family classification of the engines was developed and a tendency to use different models was seen (of different manufacturers) by different commercial airplanes. This way, the general medium values of thrust and specific consumption to sea level for each plane were obtained, and with this, the maximum FFR for each specific plane (no engine). This information can be found in the Appendix E.

With this and conducting a search of which model of mechanical and electrical pumps were used by the different models of commercial airplanes, and logically knowing their different used engines, it was possible to obtain diverse ratios between the engine flow and the flows of the pumps. With this, a lot more flexibility was achieved for the user (it is important to mention that the program is for being used in a very initial design) as just using the required FFR by the engine instead of asking for this input for each component. These ratios are the ones that will finally be implemented in the program for the calculation of the weight of the pumps, both the EDP as the different electrical (differentiating even the jettison ones, which require a bigger flow).

Is important to mention that, even though it was considered the used strategy as a good one to proceed, the lack of information in some engines added to the impossibility of knowing which pump models use certain planes, these ratios cannot be considered as totally reliable. However, it is a good way to estimate the weight of the components.

Piping

This element has been one of the most conflictive when the modelling of the weight was carried out. All the found information in the plane design books portrays these fuel lines with diameters which start from 1 inch to 4 inches. Specifically, the study of the references [22] give concrete values for some commercial airplanes.

The problem is that these studies are quite old and the values are very different from the ones found in the catalogues of actual conducts, made with flexible materials and durable. On the other hand, catalogues of refuelling hoses (the ones connected to the plane from land) show diameters of maximum values of 4” and 6” [23] clue that indicates the diameters of the fuel system, which must move a flow much lower, have decreased a lot compared to the past.

It was preferred to opt out of the old diameters and implementing the actual ones (even though that will provoke a great reduction of the weight of this component).

Another point to consider is that all the conduits are connected to all the components through the diverse fittings, besides of anchored through the internal structure of the plane each certain length. Even though diverse weights for different models of these fittings have been found, there is a lot of uncertainty of the quantity to use and which goes with each component.

In the Appendix F a great part of the EATON catalogue can be found for conduits summarised in a table form.

Sealant

There is no information about the exact points where the manufacturers apply the sealant in the wing wet tanks. Furthermore, the variety of the shape of the spars makes it even more difficult to identify where the sealant could be (because they separate the fuel tanks from the leading to the trailing edges). In the case of the ribs the variety of shapes is not important due to the fuel cross the ribs (they have holes). Figure 16 helps to follow the next ideas.

Hypothesis

- Sealant is applied along the up and down position of the front, rear and false spars (these last ones occupy a percentage of the spanwise). Then, we have two lines of sealant per main spar, in the side that conforms the integral fuel tank; and four lines in case of middle/false spars.
- Is also applied along all the contour of the wing cross-section intersected with the main spars (front and rear). This step is repeated every "rib separation" distance. A usual average rib separation is 2 ft [24]. The ribs are considered following the longitudinal direction: they do not form an angle with the longitudinal direction; it is a simplification to obtain the perimeter with the airfoil equation and does not change substantially the total length. For each rib two times, both sides.
- Although the sealant is applied along the rib perimeter, it is a good approximation, and faster for the code, to take the chord between the front and the rear spar.
- Is considered that sealant is applied along all these calculated lines with a cord area section asked as an input. Sealant applied by spots is not considered.
- The number of tanks makes no influence in the quantity of sealant in wings: separation between tanks is like another rib but in this case without holes. The sealant is still applied in the contour.
- Whether if the aircraft has cranked wing or not, the tanks are considered to be between main spars.

Once we have the total volume of sealant needed, the weight is obtained using the specific gravity that fabricant indicates [25].

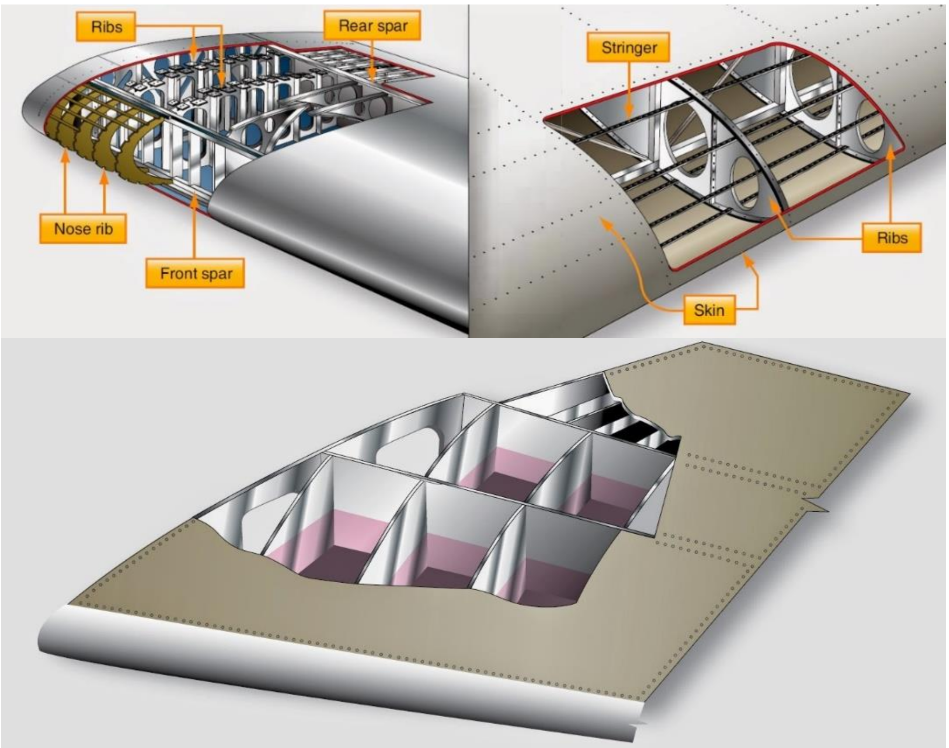

Figure 16: Wing's structure [26].
Sealant is applied along the spars and the ribs, so the fuel is confined inside the wing.

Program

Operation/Description

In this subsection, brief explanation will be given about the innerworkings of the program. Without getting deep into the calculation of every single thing nor the decisions taken, which are left out of this document. The reader can consult the Python code to better comprehend the program as this has been commented in its totality in it for an easy read about what is done in each part/line.

The code consists in broad terms of three differentiated files: the first would be the calculation module and the estimation of the fuel system, a second to draw the system and a third which contains the inputs of the plane wanting to be run (Appendix G). It was preferred that the inputs would be in an independent file, instead of been called by the main programme, for two reasons. The first, so the execution of the program was a lot faster every time that it was modified just an entry value (so it was not necessary to write every one of them one by one every time the code was executed). The second, so it was possible to have different files which would represent distinctive airplanes.

Thus, once charged the file which contains the program of the fuel system (main code) this imports the libraries necessaries for the optimal required functioning (maths, basically) and the file with the drawing module. The only thing needed then is to run the main program is the name of the file which contains all the inputs of the aircraft of interest. This file is imported and the code begins to work:

The first this program does is to check a series of conditions that must carry on in the inputs so the results make sense. These conditions are not limitations of the program but norms which have to be fulfilled for a correct design of the fuel system. Some of the things that are checked, for example, are that the number of tanks is the same or bigger to the number of engines; or that it does not make sense a compensation tank if there are engines in the tail.

The second step is to measure the volume available for the fuel. To accomplish that, basic geometry of the aircraft it is used, besides of inputs as basic as it is required, like if the user wants central tank or/and trim tank. Even though the quantity of fuel it is not part of the weight of the system, it was considered by the supervisor of the project that it was valuable data to obtain. At the end of the fuel system are a group of components which work for precisely, move and use all this amount of fuel. In addition, in the point of view of a producer, this amount of fuel, in junction with other parameters, shapes the final range of a plane, one of the most important characteristics for its sell. Lastly, it is a useful value to also check the good performance of the program by comparing it with the real values which are obtained from commercial planes.

The third step, and the most important, consists of measuring all the necessary elements according to the basic geometry and the configuration that is desired (basic inputs of the layout). This set of functions within the program englobes more than half of the code lines from the first file and obtains the number of bombs, valves and conducts. In addition, they are classified internally according to its function and the position of each of them gets stored. This will be later used for the outputs besides of the drawing of the layout

The fourth step is the measurement of the necessary volume of sealant to avoid a leak of the fuel tank.

The fifth step consists on the estimation of the weight of each component. Moreover, during this process it is measured the length of each and one of the line sections together with the measuring of the necessary information (position and weight of the component “i”) for the calculation of the centre of gravity of the fuel system.

One of the functions implemented in the programme is the measuring of the lineal pressure losses inside the fuel conducts, so that the user has an approximated idea if the diameter of the used conduct is enough for the required length and the required fuel flow rate. Anyway, it is important to mention, that these losses should be negligible depending on the importation that has been studied for the commercial diameters used and the required flows.

Lastly, every part of stored information correctly arranged and classified of the different elements which have been deemed necessary for the fuel system in study are sent in the third file (the drawing module) for, in conjunction with the geometric inputs, making a schematic representation of the obtained layout.

Outputs

Once explained the main steps for the running of the programme, it is proceeded to explain the outputs of the same.

On the one hand, and at the same time the code is running, the programme shows on the screen all the results. The time of execution is of barely a second, which means all the information comes up ready after been executed. In the Figure 18 it can be seen the obtained outputs:

```
The aircraft studied is the Airbus A380-800.

--- FUEL TANKS ---
Wings volume [L] = 330756.972148
Trim tank volume, in tail [L] = 40328.5810196
TOTAL VOLUME of FUEL [L] = 371085.553168
TOTAL WEIGHT of FUEL [kg] = 291302.159237

--- LAYOUT ---
The number of engines is 4
The nº of engine driven pumps is 4
The nº of boost pumps is 8
The nº of LP valves is 4
The nº of suction valves is 0
The nº of crossfade valves is 4
The nº of APU pumps is 1
The nº of APU LP valve(s) is 1
The nº of transfer pumps is 12
The nº of transfer valves is 23
The nº of isolation valves is 3
The nº of gravity valves (on the rib that separates two tanks) is 2
The nº of refueling points is 4
The nº of jettison valves is 2
The actual layout has 25 pumps and 43 valves.

--- WEIGHT ESTIMATION ---
The total length of piping is 440.293347267 meters with an equivalent weight of 308.205343087 kg.
The weight of the 4 engine driven pumps is 136.102665243 kg.
The weight of the electrical pumps is 130.864999723 kg.
The weight of the main valves is 66.435 kg (considering also the weight of the actuator).
The Center of Gravity is located at 16.5826148216 meters from the beginning of the root chord.
The total volume of necessary sealant is 107.275305304 L with an equivalent weight of 144.763733496 kg.
The total weight of the fuel system is 786.371741549 kg.


Velocity in the pipe is 2.51404489349 m/s
Reynolds number is 15964.1850737
Darcy friction coef. is 0.0413473534378
0.292777518009 psi/m

Do you want to draw the internal structure of the aircraft? (y/n)
y
```

Figure 18: Outputs of the program.

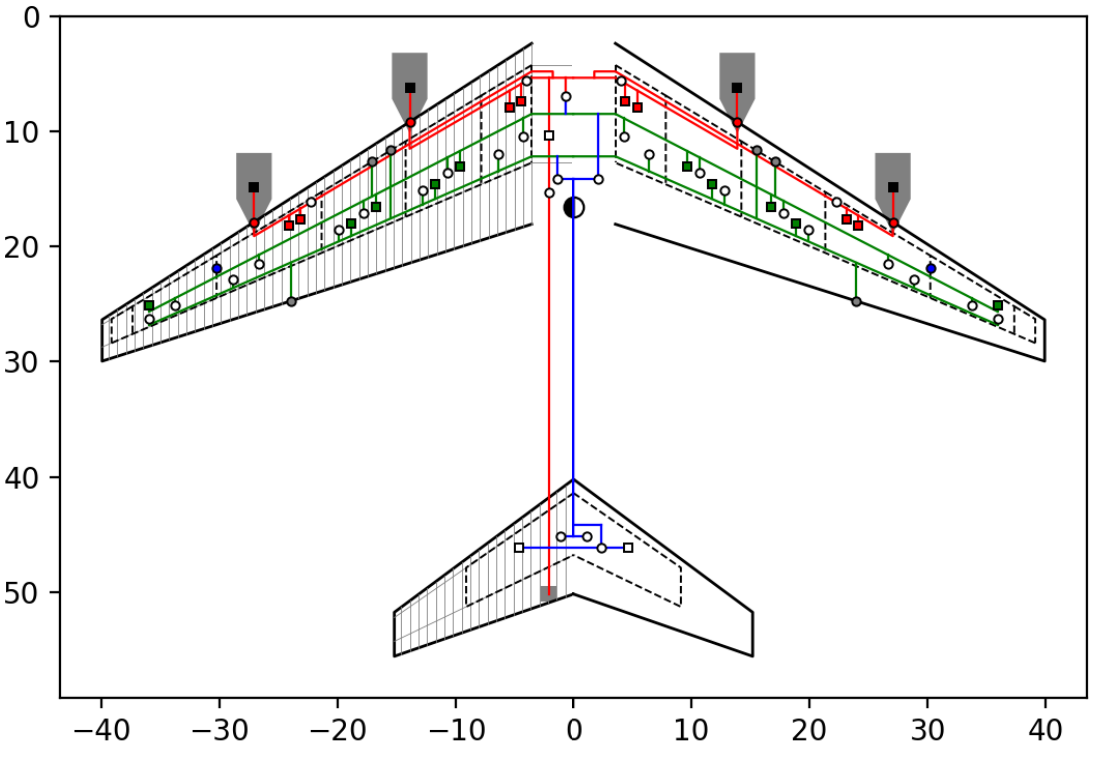

Figure 17: Layout estimated by the program. Both axes are in meters.

The first set, “Fuel Tanks”, makes reference to the approximated total space available of fuel, broken down in tanks, and its weight in kg (using the density of the kind of fuel used, which is also an input). The second set of data, “Layout”, is an exploded view of the main components. The third set “Weight Estimation”, indicates the total weight of each subset according to the classification made in the Weight estimation (7).

Finally, the programme asks the user if they want to see the internal structure of the wings and tail drawn (spars and ribs, which can also be configurated from the parameters in the file of the aircraft). In the Figure 17 the obtained layout can be observed. Is a montage which represents on its left half the exit with this activated option, while on the right half without it (less charged). This is just used to see if the distance between ribs is the proper one for the designed aircraft.

Thus, the axis of the figure represents lengths of the metric system, having the same scale in the longitudinal axis and the lateral. The understanding of the scheme is neat and clear. The shape of the wings and tail are drawn with continuous black lines, while the discontinuous black lines display the tanks in the wings (and the chosen subdivisions), centre and tail (if the plane in question relies on them). The thin grey lines represent the structural spars and ribs.

In regard to the components, a square represents a bomb while a circle represents a valve. The colour red has been chosen for the alimentation gallery, while green for the gallery of transference. The colour blue represents the isolation lines as well as the conducts inside the trim tank. It also displays the position of the centre of gravity. The complete caption is the next:

- Black square: engine driven pump.
- Red square: electrical boost driven pump
- Green and white square: electrical transfer/jettison pumps and APU pump.
- Red circle: low pressure valve.
- White circle: transfer/crosfeed/inlet/isolation electrical valve.
- Blue circle: gravity transfer valve.
- Grey circle: refuel/defuel point (in spar) or jettison ejector (trailing edge).
- Black and white big circle: center of gravity.
- Grey elements: engines and APU.

Note that the colour white has been chosen to represent elements that in principle are not working continuously.

Code limitations

Firstly, the general limitations of the code are:

- The program is only applicable to commercial airplanes.
    - Turbofan type reaction engines.
    - Integral fuel tanks.
- The development has been based on conventional aircraft. It is therefore not applicable to military aircraft, helicopters or other unconventional aircraft. Its application to new technology aircraft must be done with caution.
- You can select up to 5 fuel tanks per wing (excluding ventilation), plus one central and one compensation up to a maximum total of 12 tanks.

The limitations of the code are explained below with regard to components that cannot be calculated or estimated, based on everything read in the methodology section. They are therefore weights that exist but will not be added to the final output value of the program:

- The program does not include the weight of the ventilation system (there is not enough information available).
- The scavenge pumps cannot be sized, although they probably represent a negligible weight within the system.
- The problem with the valves was that only the main ones could be studied, but it's impossible to have the remotest idea of all the valves that exist and that do not appear in the diagrams. These non-main or safety valves are considered to have a non-negligible amount of weight. Check valves are an example.
- Both fuel management equipment and auxiliary components (strainers, primers) are totally unknown (no catalogues available).
- The path in the form of components, size and number from the EDP to the fuel injection into the combustion chamber is unknown.

Although not a code limitation, the application parameters of the sealant are unknown. This can make a big difference on the final value, the larger the aircraft, the greater the variation. With the actual inputs the program would calculate the correct amount of sealant. This is mentioned for the next stage of validation of results.

Hydraulic system

Once the fuel system was finished, the intention was to proceed in the same way as the hydraulic system. However, there were too many problems (lack of information and excessive confidentiality) to be able to develop the program successfully.

This chapter follows the same structure developed in the fuel system, explaining all the features that the program should have. However, the elements that have blocked the development of this part of the project will be highlighted. In this way it will be documented for future research lines if a code for the hydraulic system is needed.

Layout

Unlike the fuel system, the hydraulic system does not have noticeably different configurations between the different aircraft that have been analysed. This is basically because the subsystems or functions which it must supply are always the same and are in the same position. The power required will change from one plane to another (basically according to the size of the aircraft) as well the number of elements, but not the general layout. We have no option of central tanks, compensation, jettison, various forms of fuel transfer, etc.

Thus, the configuration is relatively simple. We always find the EDPs in the engines, whilst there is more flexibility of where to place the electric pumps inside the plane. The reserve tanks are located in the lower part of the fuselage, being close to the pumps of each independent system for proper suction of the hydraulic fluid. From here, and together with all the necessary valves in their relevant positions, the pressure line of each independent system is linked in parallel with all the necessary actuators. Although they never appear drawn in the general diagrams, the return line that connects all the actuators to the reservoir must not be forgotten.

In summary, it could be said that if all airplanes had the same number of subsystems and only one independent hydraulic system, the layouts would be practically identical. The variability found in the different hydraulic systems of the different aircraft lies in the connections of each independent system with the different actuators; that is, in the reliability of the system. Even so, this variability is not so great, since you can clearly identify the critical elements, such as the rudder, that need more redundancy. It's interesting to take a look at the Apendice H to see the exact layout of the Airbus A310 and the functions that covers each independent system.

In the Figure 19 below of the scheme of a Boeing 777, the connection of the elements involved in one of the three independent systems of a commercial aircraft can be clearly observed in detail. Furthermore, it is considered that the Figure 20 clearly shows the position and distribution of the three hydraulic systems in a more modest sized aircraft. This idea is the one followed by all planes, but on a larger scale.

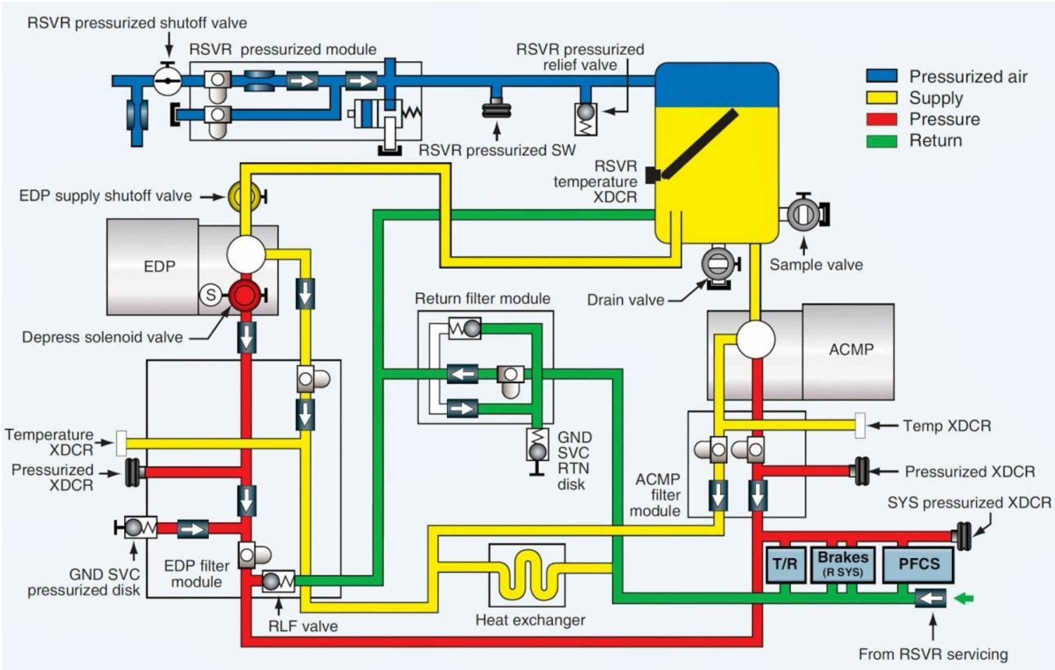

Figure 19: Right hydraulic system of a Boeing 777 [7].

Surface controls

Although the plane's control surfaces are not part of the plane as such, the actuators that move them are. They are therefore the components that generate the most impact on the normal operational functions of the aircraft, and thus should be studied and classified for later modelling.

The control surfaces are those whose position can be modified, and are therefore placed on the lifting surfaces: on wings and tail (both horizontal and vertical). Airplane control is achieved by varying the deflection of these surfaces. Its conventional classification (commercial aircraft) is as follows:

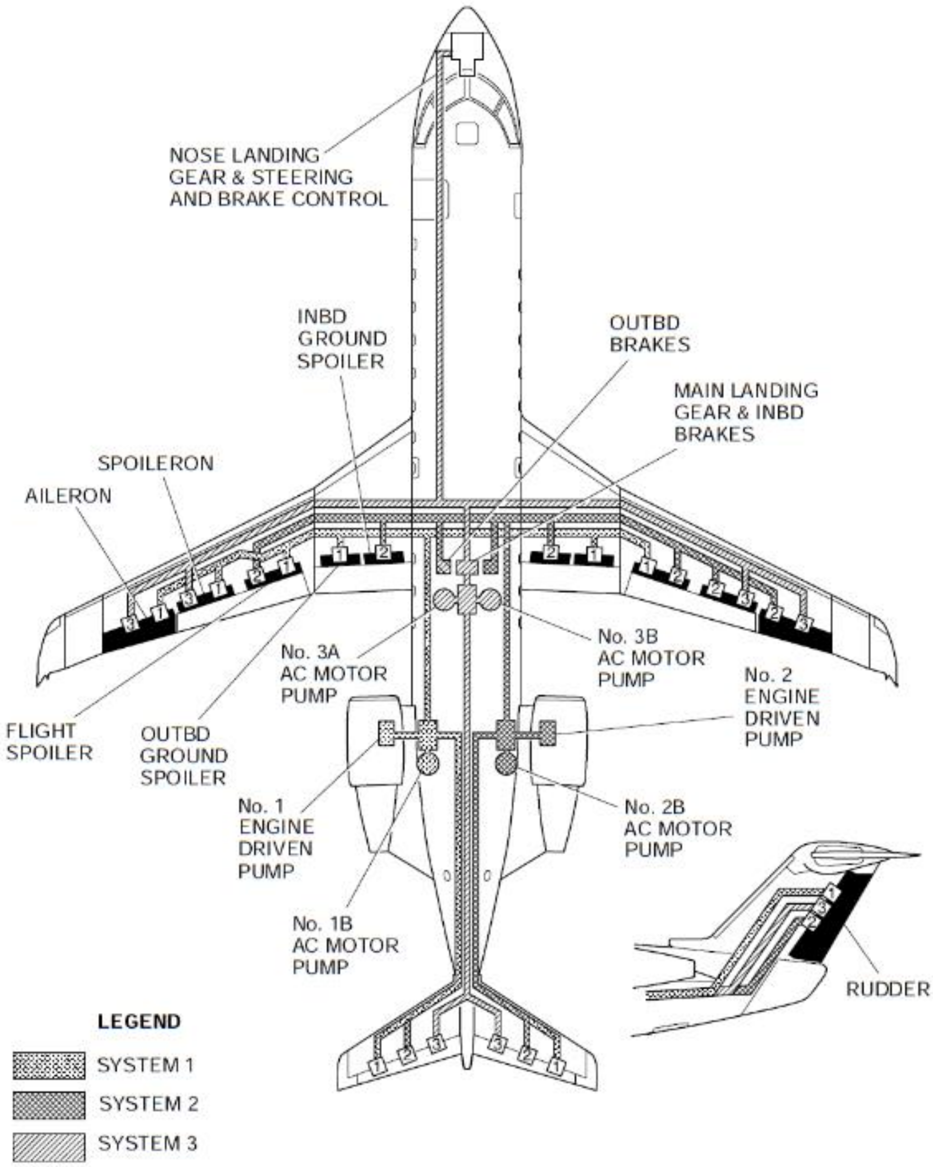

Figure 20: Hydraulic systems overview in the Bombardier CRJ100 [27].

i. Primary control surfaces: in charge of control of the flight route (pitch, roll and yaw axes).
   a. Aileron (outboard in wings): Lateral control (roll) *
   b. Elevator (horizontal tail): Longitudinal control
   c. Rudder (vertical tail): Directional control *
ii. Secondary control surfaces: reinforce primary control surface for minor or less important functions.
   a. Flap (Leading or Trailing edge; inboard)
   b. Spoiler (wings): As a brake during landing and as an auxiliary device during roll.
   c. Tab (in elevators and rudder): In the event of complete power unit failure, movement of the control surface can be affected by controlling the control tabs. Moving the control tab upsets the aerodynamic balance which causes the control surface to move.
   d. Slots (Leading edge)
   e. Slats (Leading edge)

(*) It is important to note that the lateral and directional controls are coupled to each other and therefore act together (there is an induced motion). The following Figure 21 shows in detail the control surfaces of two planes: one with wing engines and one with tail engines. Also appears the configuration of the flaps in the retracted and the extended position.

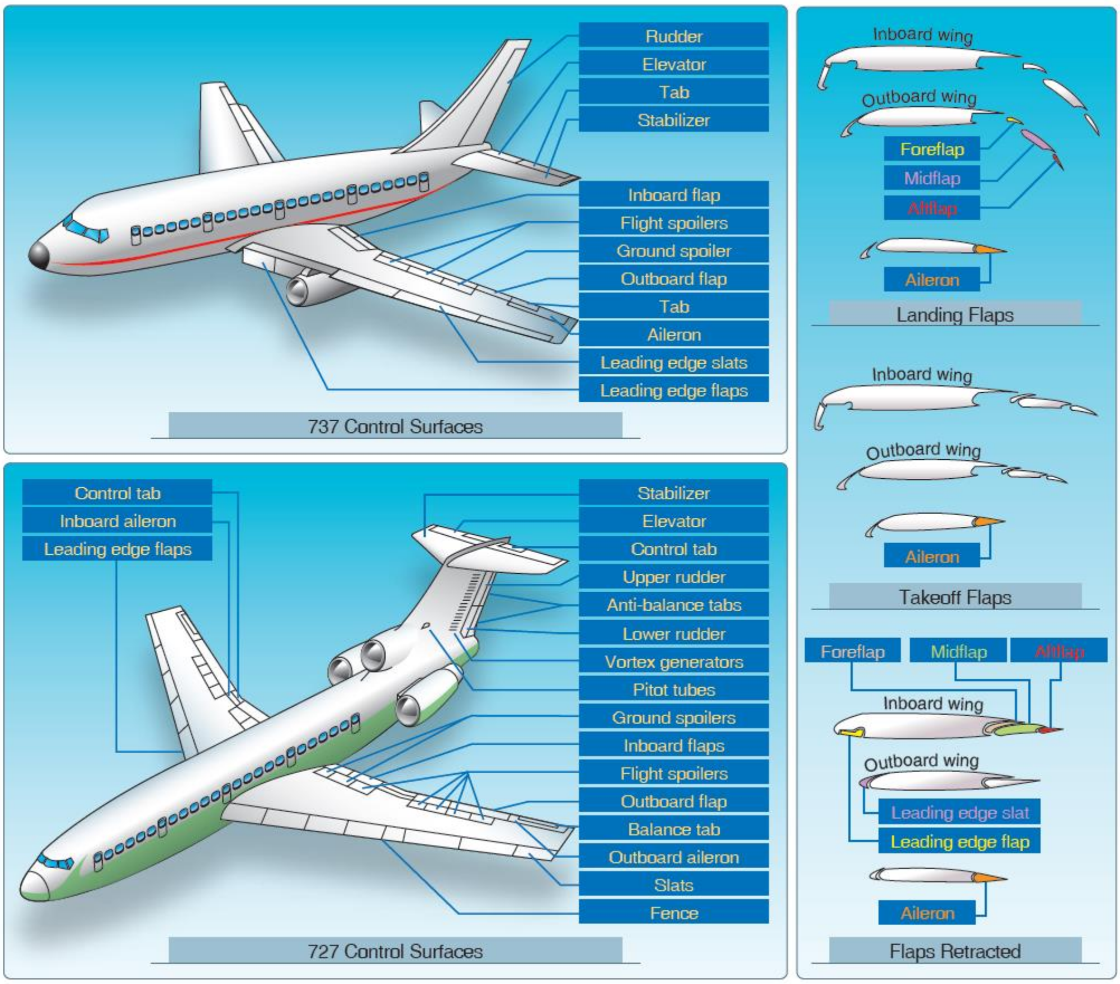

Figure 21: Control surfaces of the B727 and the B737 [28].

Weight estimation

As with the fuel system, the mass of the hydraulic system is divided into the different groups that need to be estimated in the future if the total mass of the system were to be obtained:

$$W_{h\ sys} = W_{lines} + W_{dep} + W_{pumps} + W_{valves} + W_{act} + W_{fluid} + W_{others} + W_{man} \quad (15)$$

Where:

$W_{h\ sys}$: Weight of the hydraulic system.

W_{lines}: Weight of the fluid lines.

W_{dep}: Weight of reservoirs and accumulators.

W_{pumps}: Weight of the pumps.

W_{valves}: Weight of the valves.

W_{act}: Weight of all the actuators used in the subsystems.

W_{fluid}: Weight of hydraulic fluid.

W_{others}: Weight of PTUs and filters.

W_{man}: Weight of all the components for the control and management.

Hypothesis, demonstrations and calculations

After reviewing all the information found on the web, design books, manuals and guides, this section will explain the study points followed for the model of the program, as well as the problems that arose with each component and what is needed (in the future) to be able to continue with the project.

Control surfaces

When control surfaces are deflected, the cambers of their related lifting surfaces are changed. Thus, the deflection of a control surface varies the aerodynamic forces, and consequently the result will influence the aircraft motion.

These control surfaces will be designed according to the aerodynamic requirements of the aircraft, so its size and position will be an input of the program. In terms of the hydraulic system, what is important is the hingemoment that these surfaces will produce. These moments of force of each surface will determine the actuators used in each one of them, according to the geometric configuration of the mechanism:

$$F_{surface} \cdot arm = HM \tag{16}$$

$$F_{actuator} = \frac{F_{surface}}{n^{\underline{o}}\ surf \cdot n^{\underline{o}}\ act} \tag{17}$$

These equations basically show the force that should be applied on a control surface, $F_{surface}$, is equal to the hingemoment divided by the arm of application of the actuators. In addition, it is considered that a control surface can be divided into 'n^{o} surf' different parts and that each one of them can have 'n^{o} act' actuators applying force on it. Thus, $F_{actuator}$ represents the force that only one actuator has to do.

The calculation of the hingemoment a certain control surface has to endure is as follows:

$$HM = q_{\text{màx}} \cdot C_h \cdot \int_{y1}^{y2} C_f(y)^2 \cdot \mathrm{d}y \tag{18}$$

Where:

HM: Hingemoment of the control surface (Nm).

$q_{\text{màx}}$: Maximum dynamic pressure ($\mathrm{N/m^2}$).

C_h: Control derivative of the surface.

$y1, y2$: Position of the surface in the spanwise (m).

$C_f(y)$: Chord of the control surface (plain flap) depending on the span position (m).

The control derivatives are simply the rate of change of aerodynamic forces and moments (or their coefficients) with respect to a control surface deflection. Control derivatives represent the amount of change in an aerodynamic force or moment acting on an aircraft when there is a small change in the deflection of a control surface. The greater the control derivative, the more powerful is the corresponding control surface.

All the parameters of the previous equation can be obtained, with some simplifications, in order to calculate the HM of that surface. However, it is important to specify that for the calculation of the derivative control, C_h, the maximum deflection of the control surface, δi, is necessary. These values also pose a problem when it comes to finding general valid references, since they can be very different for the same control surface from one airplane to another. In addition, the deflection of a control surface is logically linked to the design of the actuation mechanism itself, which must be done together in the design phase. The calculation of the derivative control can be found in Roskam [29].

The biggest problem appears in the total impossibility of finding the actuator arms of the cylinders. Some schematic drawings of the actuator assembly on control surfaces have been found [30], but the mechanisms vary from one to the other, without obtaining any valid conclusion. It was also tried to look for studies with average values without any success. In addition, the plane's flaps, composed of several surfaces that spread, increase this problem as they are much more complex mechanisms (see Figure 21 again).

A very interesting new approach was proposed to solve this problem. Taking into account the conservation of the power (or considering an efficiency), the necessary force to be developed by the actuator could be calculated from the average turning ratio with which it is desired to extend or retract a control surface, $\dot{\theta}$. The speed at which you want to deploy a set of control surfaces is a much more valid parameter for the initial phases of the design. So that:

$$P = HM \cdot \dot{\theta} = F \cdot v \tag{19}$$

Typical ranges of maximum control surface rates for transport flight: 100-200 deg/sec [6]. Speed, *v*, is an internal parameter of the actuator design. In normal hydraulic cylinders for example, it is around 0,5 m/s (according to several commercial catalogues observed).

It should be noted that spoilers are a somewhat different control surface as they are aerodynamic brakes. The calculation of the hingemoment for spoilers is in fact simpler and is based on the strength of drag they receive when landing.

With regard to the code, it was possible to implement the definition of all control surfaces. In order to do this, it is necessary to give the coordinates that are seen in the following Figure 22 as a percentage (in relation to spanwise and the chord) of each of the control surfaces, both on

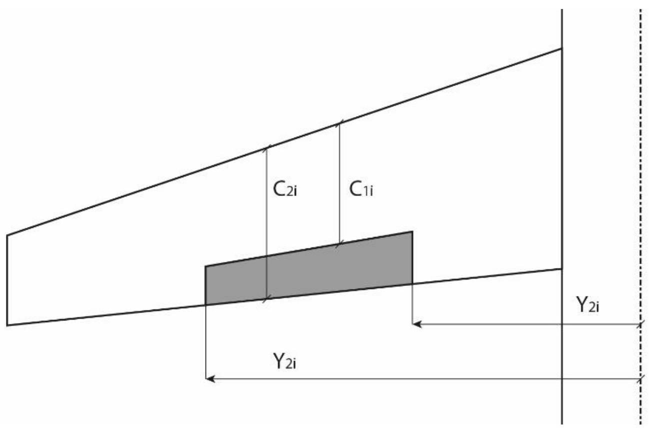

Figure 22: Necessary inputs to define the surface control "i".

one wing (the other side is symmetrical) and on the tail. The program automatically calculates the exact position. In addition, it is also necessary to state how many subsurfaces each one of these is divided by, and the number of actuators used by each system, inputs of equation 17.

Pumps

As with the fuel system, the hydraulic pump catalogues were studied to establish a relationship between their weight and their design parameters.

Engine driven pumps

In the case of pumps coupled to the engine, the conclusions that can be drawn are quite clear (in the Appendix I it can be read the summary table with the characteristics of each model). The models are numbered according to their volumetric displacement in cubic inches, which multiplied by their rotation regime (it decreases not linearly as the volumetric displacement is greater) gives us its theoretical flow. Using the efficiency of the pump we can obtain the real flow.

Although a regression curve that perfectly relates flow to weight is obtained, it remarkable that many different commercial airplanes used only two different models of these pumps, with a real flow of between 200 and 235 L/min. This suggests that manufacturers have these models of pumps customised and adapted for their aircraft in particular, since intuitively it is assumed that you would have to use one model or another according to the power that the system needs and therefore, the necessary flow to control this power.

Electrically driven pumps

Not enough electric pump models have been found to establish a relationship between weight and flow, although they function the same as the EDPs, only now the power source is electric (alternating current at 200 V / 400 Hz). In addition, of the models of pumps found, only two of them give information about their weight.

Manual pumps

There is no information for manual pumps, although this is not really a problem since commercial airplanes only use these pumps for cargo doors, which does have an implication on the total weight of the system.

Actuators

The biggest problem that has arisen in this project during the development of the hydraulic system was with the actuators. There is no information on the web regarding specific hydraulic actuators for commercial aircraft, which is a big problem since they represent a large fraction of the total weight of the system.

Trying to extrapolate the catalogues of conventional hydraulic cylinders to those used in commercial airplanes is totally useless and would result in large errors being introduced in the program and would not be correct. The actuators used by these large machines, which can be seen in some images, must be designed exactly to fulfill a certain function "X" in a plane "Y", which separate them somewhat from the conventional design of general machinery, moving on to use material that give a much better result. In fact, it is suspected that these actuators are most likely designed in conjunction with the respective function mechanisms (they are not chosen from a catalogue). In the following Figure 23 you can see quite clearly the complex network of hydraulic elements that are under the control surfaces. The actuators are marked in red.

Furthermore, without the geometric characteristics of these actuators, the amount of fluid necessary in the system cannot be calculated correctly.

Figure 23: Position of linear actuators in a wing [Source: Wikipedia].

Reservoirs and accumulators

The fact that the amount of fluid needed by each of the independent systems cannot be calculated, in turn implies the impossibility of estimating the weight of reservoirs and accumulators. Although it has not been possible to find models used by commercial airplanes (they are probably custom designed), it is clear that the size of these tanks is based on a percentage of the total fluid that is within that closed system.

Hypothesis

Regardless of all the problems involved in estimating the weight of the fuel system components, the ideas in mind are listed below, in addition to some important data found, should they be required for future projects or for the continuation of this project:

- So far, only 3 independent systems have been considered, which is the option used by all minimally large commercial aircraft.
- Each independent hydraulic system has a general pressure line and a return line. All subfunctions are in parallel.
- The total power needed by an independent system corresponds to the maximum sum of the individual powers of the functions of that system that must be operated simultaneously. It could also work with the total power and a coefficient of simultaneity. Each system, logically, must be able to perform all its functions without the help of another system under normal operating conditions.

- It is considered that if an aircraft has M independent systems with EDP as the main pump, the hydraulic system has maximum M-1 PTUs. It is also important to decide whether these PTUs are reversible or not.
- All the EDPs are always running and they have one fire shutoff valve in case of emergency. Logically an airplane has never had an EDP as backup.
- The independent systems have the same models of EDPs and ACMPs.
- It has been seen in manuals [31] that on each system, the electric pump flow is about 18% of the EDP flow capacity. It can be used to retract the surfaces but should not be used to replace the engine driven pumps. The why of this value is totally unknown.
- In a system, we do not have actuators as backups that are not working (when activating one of the subfunctions) waiting for the loss of one of the operating actuators. It is a redundancy that is only useful if the actuator fails (since the general line is shared and if it fails the backup actuator would also be inoperative) and would also add too much extra weight. Redundancy is already sufficiently covered with independent systems.

Program

Operation/Description

Although the program for the hydraulic system has not been done because it was not possible to advance further in the project with the time available, and because of all the problems discussed in the previous section, it did count the distribution of the three hydraulic systems to the control surfaces.

The program was expected to function in the same way as the fuel system: three files (main program, inputs and drawing module).

So the program calculates and places each of the control surfaces in their corresponding position, in addition to calculating their area. Then using as reference the criticality and redundancy analysis of each subsystem (can be found in Appendix J) it places the necessary actuators on each surface and links them with the relevant independent systems.

Outputs

The result of the operation explained in the previous subsection can be seen in the following Figure 24:

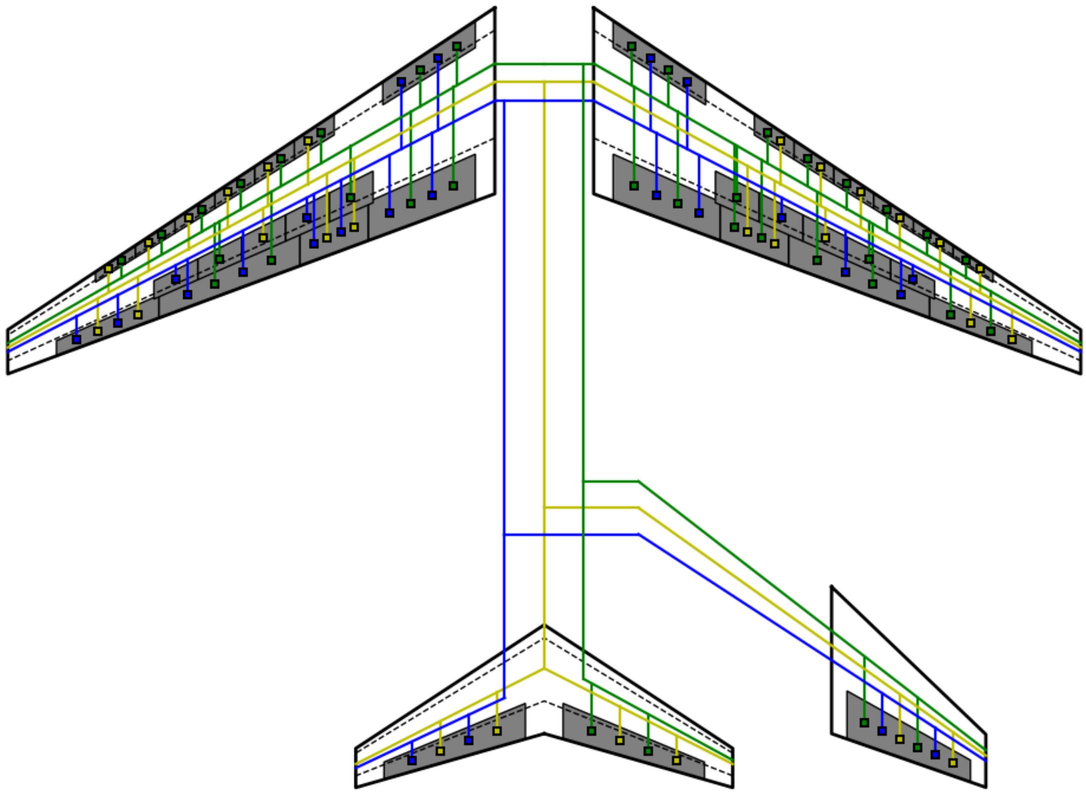

Figure 24: Hydraulic systems obtained by the program.

The three independent systems are represented with the colours blue, green and yellow. As an example, it shows that each system links two actuators ('nº act') for each control surface included in the group that particular system must supply. It can be observed, also, how each spoiler is activated only by one system, and how the rudder has the 3 systems connected. The slats in the leading edge are a good example to know how works the definition of subsurfaces: the user has to introduce the 4 inputs explained before of the total desired area and then select the 'nº surf', 6 in this case.

Future of the program

There are no limitations of the code for the hydraulic system as such since it is unfinished. Future lines of research should work to solve the main problems discussed above and then proceed with the development of a first version of the program.

In addition, here are two ideas that could be studied as alternatives to the conventional hydraulic system:

1. The first would be to separate all control surfaces into subsurfaces all of the same size. The idea would be to use the same actuator in all of them, being able to simplify the design of the mechanism in addition to reducing manufacturing costs (only one type of actuator is purchased).
2. The second would be to compare the conventional hydraulic system with an electro-hydraulic system formed only by electrohydraulic actuators since it is believed that this system is the future for commercial airplanes. For example, the Boeing 787 is the first aircraft designed with more electrical systems than hydraulic systems.

Results and Analysis

Before drawing conclusions, the last chapter of the project will obviously only focus on the fuel system of the aircraft, since as we have seen it is the only one that could be completed.

So it is divided into two sections, the first part to validate the correct internal functioning of the program, and the second that consists in executing the code for various commercial airplanes and analyzing the results obtained.

Validation of the program

To validate the program, the best way considered to do so was to simulate a base plane and from there vary key parameters to observe how the program adapted to these changes. Therefore, the objective is to verify that the results obtained are realistic with each change made.

As a starting point there is a description of the basic layout (adapted from the Airbus A330-200), an aircraft that is 60 m long, with a fuselage diameter of 5,6 m. It has an aspect ratio of 10 and a wingspan of 60 m. It has two tanks in each wing, in addition to the ventilation and central tank. It should be clarified that the ventilation tanks are not counted from here onwards (so in this case we have 4 + 1). The two engines under wings require a fuel flow of 3 kg/s each. The APU is in the tail.

Although many tests have been done to validate the code is consistent with itself, here is a summary of some of the most significant ones, so as not to lengthen the chapter excessively. The modifications with respect to the base layout have been made in a way that several inputs were not changed at the same time as they could confuse the reading of the results. All the parameters that the program needs and that are not explicitly cited are logically maintained with the same value when passing from one modification to another. In Table 1 it can be found a summary of the validation.

Modification 1:

The first modification is basically to double the size of the plane. The distance inputs have therefore been multiplied by 2, in addition to the separation between internal ribs, to maintain the proportions.

The results show that effectively the volume of fuel is increased by a factor of 8 (3 dimensions) and the amount of sealant is also doubled (logically the same cord has been considered). The total length of ducts is also almost double. This very small difference is due only to connections with EDPs (which are the same length).

Modification 2:

The second modification adds a compensation tank in the tail.

This logically implies an increase in fuel capacity (not very large, some 8000 L, since the trim tanks are small), in addition to an increase in piping length. It can be seen that this length is approximately 30 m, half the length of the plane. So the length between the fuel line to the tail plus the relevant connections are checked (with the valves and the transfer gallery). The amount of sealant is also now taken into consideration as there is a tank in the tail to seal.

Modification 3:

In the third modification, two independent parameters have been changed at the same time, on the one hand the space for the fuel system has been narrowed by moving the two main spars, and on the other an auxiliary boost pump has been added.

The results show clearly the plane now has much less fuel capacity. It can also be seen that although the “available chord” has been reduced by 28% ((30-12) + (70-60)), the fuel capacity has been reduced by 47%. This is logical and demonstrates how the program follows the perimeter of the airfoil, where the beginning of the wing is much thicker than at the end. Advancing the front spar, therefore, we lose much more fuel capacity than setting back the rear spar to the same extent.
In addition, there are two more electric pumps, one per motor. The length of the ducts has not been highlighted since, although the value varies slightly, this is due to the adjustment for the new position that the galleries now occupy, which limits the available space.

Modification 4:

The fourth modification adds 3 more tanks per wing. In other words the same space that used to house 2 tanks now houses 5. Increasing the number of tanks in reality is to improve the reliability of the system.

It can be seen how the number of necessary components has increased, both electric pumps and valves. The length of ducts has also increased a bit because of the necessity to connect all these new elements.

Modification 5:

The fifth modification gives the system up to 2 transfer galleries, as can be seen working in the great Airbus A380.

Logically the number of electric pumps and valves increases. With regard to the length of ducts, it can be seen how it has increased approximately by adding the wingspan of the plane (60 m approximately) - the gallery does not cover the entire wingspan of the plane, but it has the sweep angle, in addition to some connections.

Modification 6:

The sixth modification adds two more engines to the plane, one on each wing, plus an independent feed (that do not share the same line).

This implies 2 extra EDPs (1 per engine) and 4 more electric pumps boost (2 for each new engine), plus 5 more valves: 1 low pressure valve for each new engine and the valve that previously allowed feeding between sides was replaced by 4 valves that allow cross-feed between all engines. The length has increased by having more feed lines.

Although it is not shown in the table, if modification 6 is executed but without an independent feed supply to each engine, 19 valves are obtained (a difference of 3 mentioned compared to the above mentioned) and the piping distance is somewhere between the basic layout and modification 5.

Modification 7:

The seventh modification only increases the fuel flow needed by each engine.

As can be seen in the results, the only parameter that has been modified is the weight, whilst the corresponding results for the layout are exactly the same. This modification of the weight is nothing more than the increase in the unit weight of the pumps (EDPs and electric) as it now has to move a greater flow. More power is required.

Table 1: Comparison between the basic layout and its respective modifications.

Variable	Basic	M1	M2	M3	M4	M5	M6	M7
GEOMETRY								
L [m]	60	**120**	60	60	60	60	60	60
Width fus. [m]	5,6	**11,2**	5,6	5,6	5,6	5,6	5,6	5,6
AR	10	10	10	10	10	10	10	10
Span [m]	60	**120**	60	60	60	60	60	60
Taper ratio	0,25	0,25	0,25	0,25	0,25	0,25	0,25	0,25
thickness	11	11	11	11	11	11	11	11
Sweep [º]	30,0	30,0	30,0	30,0	30,0	30,0	30,0	30,0
Front spar [%]	12	12	12	**30**	12	12	12	12
Rear spar [%]	70	70	70	**60**	70	70	70	70
ENGINES								
Nº eng. Wings	2	2	2	2	2	2	**4**	2
Nº eng. Tail	0	0	0	0	0	0	0	0
FFR [kg/s]	3	3	3	3	3	3	3	**5**
APU								
APU position	Tail	Tail	Tail	Tail	Tail	Tail	Tail	Tail
APU shared	No	No	No	No	No	No	No	No
FUEL LAYOUT								
Indep.	-	-	-	-	-	-	**Yes**	-
Nº Tanks	5	5	5	5	**11**	5	5	5
Center Tank	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Trim Tank	No	No	**Yes**	No	No	No	No	No
Nº galleries	1	1	1	1	1	**2**	1	1
Aux. pumps	0	0	0	**1**	0	0	0	0
DB Ribs [m]	0,7	**1,4**	0,7	0,7	0,7	0,7	0,7	0,7
OUTPUTS								
Fuel vol. [L]	114318	**914549**	**122667**	**60572**	114318	114318	114318	114318
Nº EDP	2	2	2	2	2	2	**4**	2
Nº Elect.	7	7	**8**	**9**	**13**	**11**	**11**	7
Nº Valves	17	17	**20**	17	**23**	**24**	**22**	17
L piping [m]	154,6	**303,2**	**185,6**	149	**170,6**	**216**	**213,3**	154,6
Sealant [L]	72	**144**	**84**	**48**	72	72	72	72
T. weight [kg]	325,3	**526,8**	**373,9**	**300,6**	**378,6**	**401**	**451**	**361,9**

The layouts that the program has given as output for each modification, in addition to the basic system, have not been attached here so as not to overload the reader with information.

Comparison with commercial airplanes

In this second part, once it has been verified that the program works with coherence when adapting to changes in variables, it remains to be seen how it estimates the layouts and the total weight of different commercial aircraft.

For this, and although for the testing and improvement of the program even more airplanes were used, this section of results will include those that have enough information to configure their internal layout options. The planes that have been chosen are the following:

- Airbus A310-300
- Airbus A320-200
- Airbus A330-200
- Airbus A340-300
- Airbus A380-800
- McDonnell Douglas DC-10-40
- Boeing 727-200 Advanced
- Boeing 737-200
- Boeing 747-400
- Embraer ERJ145

Firstly, the layout of each commercial aircraft was visually compared with the layout obtained by the program and also in terms of number and position of elements. The objective was that the number of components used to be similar, although their position could vary, since each manufacturer uses its own methodology. The reader should be reminded that the layouts of different aircraft can be found in Appendix K, whilst the layouts obtained by the program are shown in Appendix L.

Finally, once the program has been run on all the sample airplanes chosen, the numerical outputs obtained for each of them are attached in the summary Table 2 together with the fuel system weight estimates made by the formulas explained in the Literature Review chapter, as well as the fuel capacity values obtained from manufacturers [32] [33].

It is important to comment that the program has been run on all the models using the same values with regard to the parameters that present uncertainty, such as for example the sealant cord or the distance between ribs. Although these values are certainly incorrect with respect to the actual values, the same are used throughout so that this variability does not influence or affect the lecture of the results. In practice it is assumed these values should not be very different between one aircraft and another.

Table 2: Results of the program for several airplanes and comparison with other methods.

	A310-300	A320-200	A330-200	A340-300	A380-800	DC-10-40	B727-200Adv	B737-200	B747-400	ERJ145
Fuel capacity (reality) [L]										
Total	**61090**	**23858**	**139090**	**141500**	**330540**	**100691**	**28729**	**20103**	**216389**	**5146**
Fuel results (program) [L]										
Wings	38471,8	17287,2	89383,05	89383,05	313377	83097,67	25231,7	12634,2	145553	5079,26
Center tank	15862,3	6574,5	26606,10	26606,10	0	33469,83	8330,15	5420,93	46583	0
Trim tank	6959,6	0	8427,50	8427,50	38760	0	0	0	20566	0
Total	**61293,7**	**23861,7**	**124416,65**	**124416,65**	**352137**	**116567,5**	**33561,85**	**18055,13**	**212702**	**5079,26**
Layout's components (program)										
Nº of EDP	2	2	2	4	4	3	3	2	4	2
Nº EMDP	12	7	11	13	21	7	9	7	12	7
Nº of valves	18	18	21	28	43	19	15	12	27	8
Length of piping [m]	160,11	85,02	167,74	223,64	440,3	175,17	147,67	75,85	300,95	79,78
Sealant [L]	50,25	29,05	85,17	85,17	167,48	61,85	32,61	26,19	116,16	19,85
Weight breakdown (program) [kg]										
Fuel piping	112,08	59,52	117,418	156,54	308,21	122,62	103,37	53,10	210,67	55,85
EDP	46,66	30,07	55,95	69,79	136,10	70,87	44,16	29,57	111,95	20,32
EMDP	61,2	28,11	60,78	55,86	130,86	35,12	35,94	28,01	66,86	24,18
Valves (main)	27,8	27,81	32,45	43,26	66,44	29,35	23,18	18,54	41,715	12,36
Sealant	67,84	39,21	114,97	114,97	226,10	83,49	44,02	35,35	156,81	26,80
Total	**315,58**	**184,72**	**381,57**	**440,43**	**867,71**	**341,46**	**250,66**	**164,57**	**588,00**	**139,50**
Weight estimation (literature review) [kg]										
Torenbeek [11]	673,75	497,91	806,02	881,78	1505,16	706,54	412,31	350,14	1137,64	215,19
NASA [12]	511,14	290,66	821,28	1117,54	1849,43	817,01	402,17	272,54	1456,88	118,57
Raymer [10]	474,01	244,76	780,42	788,58	1785,50	585,74	212,18	170,90	1177,90	61,11
Roskam [34]						1954	518	260,82	1053	
Ratio	1,75	1,86	2,10	2,11	1,97	2,06	1,37	1,61	2,14	0,94

Analysis of the results obtained shown in the table:

With regard to fuel capacity, it can be confirmed that the program very satisfactorily estimates the maximum amount available according to the geometry of the aircraft and based on the assumptions made. Some planes obtain more accurate results than others. It should be noted, however, that the estimated volumes for the trim tanks in tail are always greater than the real ones. This clearly indicates that the consideration that they cover 60% of the tail span is too much, or that the tail spars are even closer to each other. In any case, this is indicative as the program calculates the maximum volume available with the geometry entered. From that maximum volume the manufacturer can then decide whether to use everything for fuel or not, and also whether they have to place additional tanks to increase the range of the aircraft.

Moving on to the number of components, it is clear to see what has already been shown step by step in the previous subsection. The program clearly adapts to the complexity of the aircraft introduced. In the case of ERJ145 or B737, small aircraft with low distribution complexity. Next come the bulk of aircraft examined, with an increase in both the number of valves and electric pumps. Finally, it is reached the largest aircraft, the A380, where it is verified how its second gallery significantly increases the number of components used. The simulated B747 distances a little from the real scheme as it is a strange case where the manufacturer also places transfer pumps in 2 of the feed tanks.

We reach the final point of the project: the comparison of the estimated weight values of the fuel system. The weight values obtained from the references found will be discussed first, and then compared with those obtained by the program. As a reminder, the three formulas for Torenbeek, NASA and Raymer are, respectively:

$$W_{fuel\,system} = 36{,}3 \cdot \left(N_{eng} + N_{ft} - 1\right) + 4{,}366 \cdot {N_{ft}}^{0{,}5} \cdot {V_{ft}}^{0{,}333} \tag{4}$$

$$W_{fuel\,system} = 1{,}07 \cdot {W_{fuel\,cap}}^{0{,}58} \cdot {N_{eng}}^{0{,}43} \cdot {V_{max}}^{0{,}34} \tag{5}$$

$$W_{fuel\,system} = 2{,}405 \cdot {V_t}^{0{,}606} \cdot \frac{1}{2} \cdot {N_t}^{0{,}5} \tag{3}$$

The estimates of Torenbeek and NASA are more or less even in all models. It can be clearly seen that, although both use fuel capacity as a parameter, NASA's formula gives values higher than Torenbeeks in larger aircraft: when the capacity barrier of approximately 120.000 L is exceeded, this parameter has a big influence on the formula used by NASA.

It is also important to comment that another of the parameters used by NASA is the maximum speed, in the form of a Mach number. All commercial airplanes have similar values for this variable (except the ERJ145, which is clearly a much smaller aircraft), which is not considered as an input of great influence for commercial aircrafts.

Taking into account that the last parameter used by NASA is the number of engines, which at present can be 2, 3 or 4, it can be said that more or less all the work of NASA statistics is based on the size of the airplane, or its wingspan, as the basic parameter for determining the weight of the system. Although the formula may or may not be very precise with respect to the actual values (not even the correlation coefficient is indicated), the only weights that increase proportionally with the size are the amount of sealant and the length of ducts. Although in practice it can be shown that a greater size entails more complexity, this increase in size by itself does not require us to use more components or make the system more redundant if it is not decided to do so.

With the Torenbeek formula, in addition to the fuel capacity and the number of engines, it uses the number of tanks, which is a parameter that implies more or less complexity (and more components) in the fuel system.

Raymer's formula also uses the number of tanks as a parameter, but ignores the number of mounted engines. Like the previous two, it also uses the maximum capacity.

It is important to comment that the Roskam values will not be taken into account because there is not sufficient data regarding the fuel system, nor the weight values of the aircraft from the group tested. It is also considered that the value of 1954 kg for the DC-10-30 model is incorrect since it is too large for the characteristics of the aircraft. It has a greater weight than the one given for the B747 (a larger and more complex aircraft) and also distances itself from the formulas of Torenbeek, NASA and Raymer, whilst the order of magnitude matches in the other models.

Having discussed the previous formulas, it is time to compare them with the values obtained using the program. It can clearly be said that this first version of the program greatly underestimates the weight of the fuel system. This is logical, since all the restrictions mentioned in the subsection of Code Limitations (not repeated here so as not to lengthen the document) contribute to not adding weight to the total. It should be mentioned that the sealant represents one of the main components of great uncertainty within the fuel system. Just as pumps and valves are considered well estimated, the sealant can reduce or greatly increase the total weight just by modifying the "cord area" parameter.

The tendency of the program is as follows: the smaller the plane, the less difference there is between the obtained and objective values (those estimated by the formula, since there are no real values). In fact, in the case of ERJ145 the program gives a total weight value greater than the estimates of NASA and Raymer (which clearly demonstrates they do not adapt well to very small aircraft). As the size of the airplanes increases, there is a greater difference between the values of the program and the real ones. This can be seen in the last row of the table, "Ratio", which is the division between the average of the 3 estimates with the value obtained by the program. This behavior supports the idea that the underestimation of the weight comes from the lack of some components, which increase, the larger the plane.
One of the benefits of the program should be highlighted: in the case of the Airbus A380 this ratio, instead of increasing a little (more than the one that the B747 has), breaks the trend and decreases. It is the only plane with a double transfer gallery. For all three formulas, it is simply a larger aircraft, whilst the program is capable of increasing the weight according to its greater complexity (for this reason the ratio does not follow the increasing trend).

However, although the values obtained are far from the supposed objective, the program is considered to be very robust to the layout changes introduced. If the program weight outputs are plotted against the estimates of each of the formulas, it can be seen that despite the great precision error, there is a very high correlation between them, which implies that the program is adapting correctly to the variation of the systems. Figure 25, 26 and 27 show these correlations:

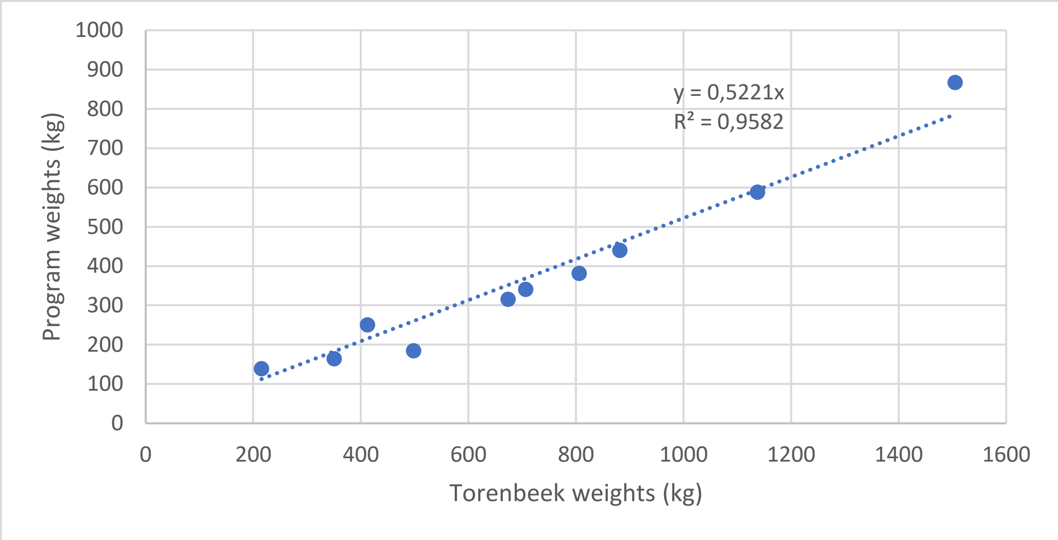

Figure 25: Torenbeek vs. Program weights.

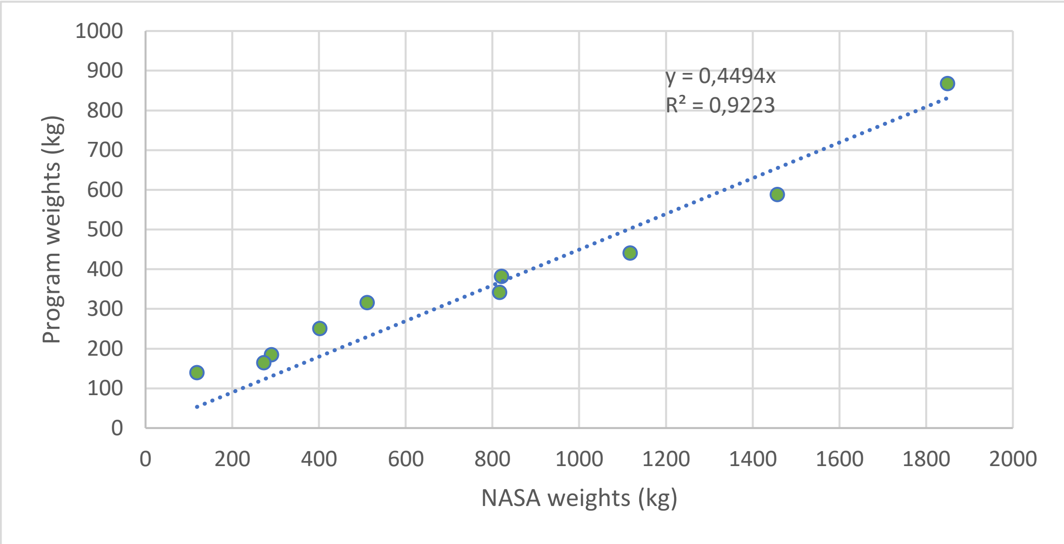

Figure 26: NASA vs. Program weights.

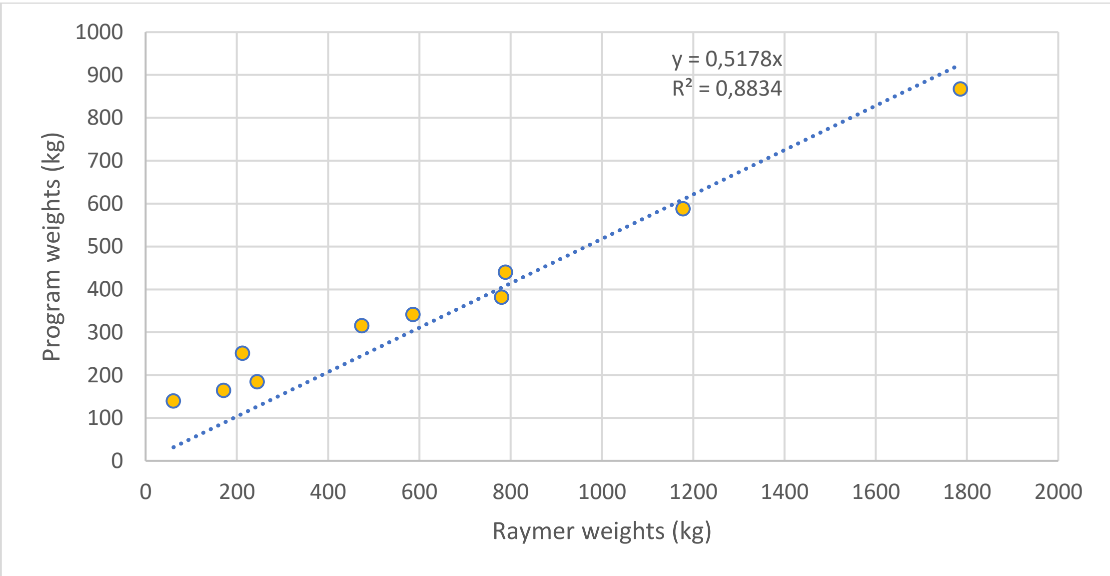

Figure 27: Raymer vs. Program weights.

In addition, if the same graph is repeated, but this time with the average of the three estimates, a correlation coefficient R^2 of 0,9613 is achieved, as can be seen in Figure 28.

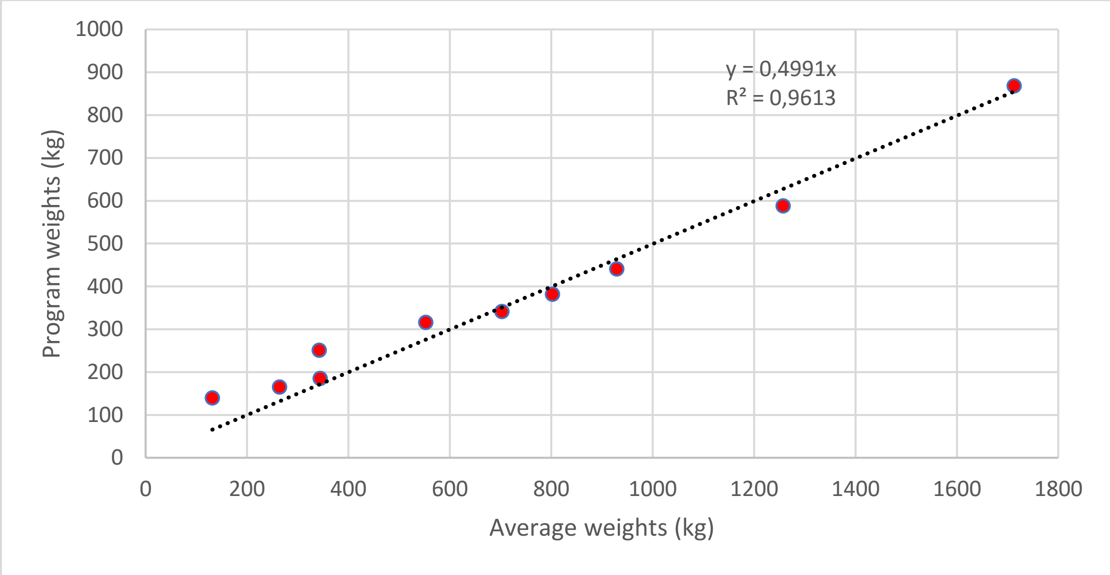

Figure 28: Average (Torenbeek, NASA and Raymer) vs. Program weights.

It was suggested that a good way to bring the value obtained closer to the objective would be to determine weight coefficients, a function of the outputs that can be obtained, that represent all the elements from which information cannot be obtained at present. For example, that the check valves are a function of the number of components and fuel lines; or that the ventilation system is a function of the size and number of tanks. In this way, it would not be necessary to model them. However, it is necessary to achieve this to have real values of how the weight within the fuel system is subdivided for each of the groups (or components), since these coefficients cannot be estimated reliably.

Finally, to highlight the opinion that although the total weight is clearly underestimated, it is considered that the current weight of the new fuel systems is less than the values that are given in design books or formulas such as those previously mentioned. This is so for one reason: development of materials over the years has allowed a reduction in the weight of almost all system components. This reduction does not necessarily imply a reduction in aircraft weight, since these improvements are often used in other systems to increase the electrical system, which both the space and automobile industries are betting on.

Conclusions

The main objective of this project has been met - to design a parametric program to obtain the weight of the fuel system of commercial aircraft. As mentioned throughout the document and based on the results section, two conclusions can be obtained:

Firstly, at this moment in time, it is not a better tool for calculating weight than current formulas, which are also simpler.

Secondly it offers greater flexibility and adaptability to different types of aircraft and their internal design.

However, completing the program to eliminate its existing limitations and its implementation could result in much more precise numerical results that, together with the ability of the program to give more flexibility to the user, could become an interesting tool for the initial phase of the fuel system design. The options to customize, and the representation of the configured layout also provide a useful improvement over the usual formulas.

With regards to the hydraulic system, future lines of work should seek to obtain all this confidential or unavailable information that prevents the project from progressing now.

The key to perfecting both systems would be to have a large collection of real data of the exact weights of each subsystem, in addition to the different components used. This would allow a perfect model of the system as well as a great tool to validate and polish the code.

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Appendices

Appendix A. Fuel components

	AIRBUS											
	A310			A320			A330			A340-300		
ITEM	Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS
Nº engines				**2**			**2**			**4**		
Inner Tanks	2	27900	Fuel transfers between wing and center tank are possible on ground only	2	13848		2	84000	With division (valves normally opened); with collector cell	2	85550	With division; with 2 collector cell, 1 per engine
Outer Tanks	2	7400		2	1760	by gravity	2	7300	by gravity	2	7300	by gravity
Mid tank (not usual)												
Wing Tanks (exc. vent)	4	35300		4	15608	0	4	91300		4	92850	
Center Tank	1	19640		1	8250		1	41560		1	42420	
Trim tank (THS)	1	6150		0			1	6230		1	6230	
Tanks	**5**	**61090**		**5**	**23858**	**0**	**6**	**139090**		**6**	**141500**	
Engine driven pump*				4			4			8		
Auxiliary pumps				0			2			0		
Transfer pumps	12			2			3			3		
APU Pump	1		supplied from the left	1			2			2		
Fuel Pumps	**13**			**7**		**4xINR TK; 2xCTR TK**	**11**			**13**		
Transfer Valves	6			5		Electrical; 1 for defueling	5			5		
Cross Fade Valve	1			1			1			4		
Isolation Valve (Trim)	5			0			2			2		
Inlet Valve	6			3			6			6		
Jettison Valve	0			0			2			2		
Engine LP Valve	2			2			2			4		
Non-return valves	13			0			3			4		
Suction Valve	0			4		Feed by gravity (FP Wings)	0			0		
APU Valves	1			1		LP	2		LP + isol (FWD/AFT)	2		LP + isol (FWD/AFT)
Refuelling points (valves)	2			2			2			2		
Nº of galleries	2			2		Feed/XFR and refuelling	2		Feed and refuelling	2		Feed and refuelling
Valves (except non-return)	**23**			**18**			**22**			**27**		

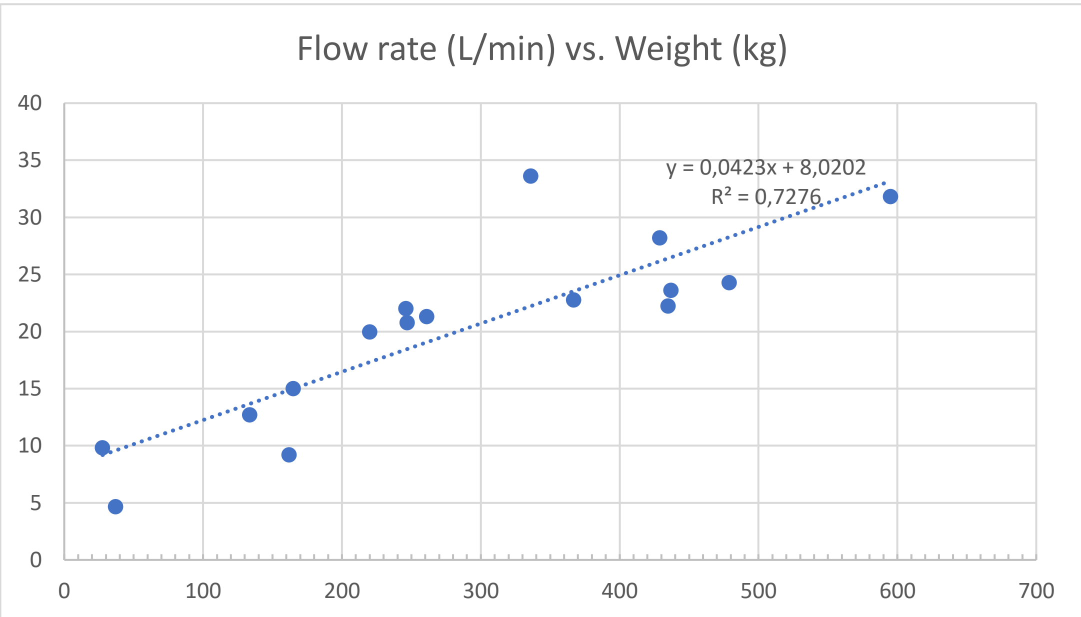
*One pump is capable of suplly all the engines IN CRUISE with the crossfade valve open

			BOEING									
A380			727			747			DC-10			
Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS	Qt	Cy	OBSERVATIONS
4			**3**		**In the tail**	**4**			**3**		**2 on wings; 1 on tail**
4	150960	Feed tank inner engines included	0			2			0		The center tank occupy the inner part of the wings.
2	21040		2	13574		2			2	45424	
4	134840	Another feed tank inc.				2					
10	306840		2	13574		6	0		2	45424	
0			1	15155	Intengral+Removable	1			1	91985	
1	23700		0			1					
11	**330540**		**3**	**28729**		**8**	**0**		**3**	**137409**	
8			6			8			6		
0			0			1		Scavenge Pump	0		
12						8					
1			¿?			1			1		¿?
21			**6**			**18**			**10**		**Considering APU sep.**
3		1 for transfer/defuel valve	4		Not transfer of fuel during the flight	12					Share with refuel?
4			3			4			3		
3		2 transfer galleries				4					
22			4		1 valve manual for defuel.	11			3		
2			2			2			2		
4			3			4			5		Engine 2 have 3???
0						0					
2		Only link with forward	1			1			1		
4		2 ref. points + 2 valves for feed both galleries	1		In right wing; 2 entrances	2			4		
3		Transfer: Aft+Forward	3		Feed, refuelling and vent				2,5		Feed, refuel/transfer
44			**18**			**40**			**18**		

Appendix B: EDP (fuel system)

Models -->	704300, 708300, 708400, 708600, 714900	724400	828300	828500	838000	721400	830800	830100*
ID number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Speed (rpm)	6000	6250	6250	7380	7863	6841	7088	6228
Inlet pressure (psi)	30	30	30	15	20	20	20	
Inlet pressure (kPa)	206,85	206,85	206,85	103,425	137,9	137,9	137,9	0
Boost Stage press rise (psi)	140	140	110			160		130
Boost Stage press rise (kPa)	965,3	965,3	758,45	0	0	1103,2	0	896,35
Discharge pressure (psi)	1000	1145	1145	1600	1700	1630	1731	1210
Discharge pressure (kPa)	6895	7894,775	7894,775	11032	11721,5	11238,85	11935,245	8342,95
FFR (l/min)	220	247	246	429	595	435	479	27,6
FFR (l/s)	3,666666667	4,1166667	4,1	7,15	9,9166667	7,25	7,9833333	0,46
FFR (kg/s)	2,878333333	3,2315833	3,2185	5,61275	7,7845833	5,69125	6,2669167	0,3611
Weight (pounds)	44	45,75	48,4	62,2	70,2	49	53,5	21,5
Weight (kg)	19,95	20,76	22	28,2	31,8	22,23	24,27	9,8
Engine model or family	CFM56-2/3/5	CFM56-5	CFM56-7	GE 90-76/ 77-85-90-92-94	GE 90-112/115	Trent 768, 772, 877, 884, 892, 892B	Trent 895	RB211-535

Models -->	825500	723300	828200, 831000	715200	373400, 382400, 389400, 705300, 705400, 705500, 706800, 715000**	386900, 390600, 720500, 720600, 833700, 833800**	243600, 358200, 378200, 371900, 835800	384300, 835900	829500
ID number	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Speed (rpm)	6850	7145	8400	4200	6000	6000	4200	4200	8319
Inlet pressure (psi)	20	20	30	15	20	20	20	20	20
Inlet pressure (kPa)	137,9	137,9	206,85	103,425	137,9	137,9	137,9	137,9	137,9
Boost Stage press rise (psi)	160	200	150						
Boost Stage press rise (kPa)	1103,2	1379	1034,25	0	0	0	0	0	0
Discharge pressure (psi)	1235	1355	1350	665	1100	1100	900	1000	800
Discharge pressure (kPa)	8515,325	9342,725	9308,25	4585,175	7584,5	7584,5	6205,5	6895	5516
FFR (l/min)	367	437	162	37,1	261	336	133,5	165	108
FFR (l/s)	6,1166667	7,2833333	2,7	0,6183333	4,35	5,6	2,225	2,75	1,8
FFR (kg/s)	4,8015833	5,7174167	2,1195	0,4853917	3,41475	4,396	1,746625	2,15875	1,413
Weight (pounds)	50	52	20,3	10,25	47	74	28	33	
Weight (kg)	22,76	23,6	9,2	4,65	21,3	33,6	12,7	15	-
Engine model or family	PW Series 4000	PW Series 4000	BR710, BR715	PW901A	JT9D	JT9D-59, JT9D-70, JT9D-7Q	JT8D-1/7/9/11/15	JT8D-17/209/219	CF34-8C, CF34-8E
							Look the same model		



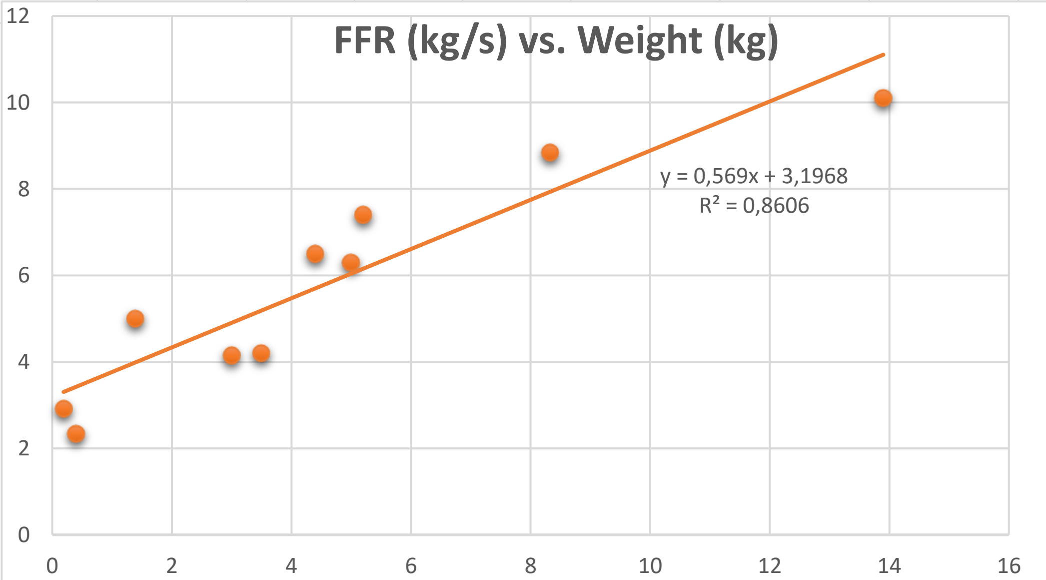
Appendix C: Electrically driven pumps (fuel system)

This sheet contains the data file for EATON auxiliary/boost/transfer pumps; electrically (AC/DC) driven. I have saved the catalogues with the typical performance curves.

	Civil airplanes										
Model:	**20026**	**9121**	**20004**	**8410**	**8810**	**9106**	**9602**	**20002**	**9108**	**39-0002**	**39-0001**
Power supply [V]	18-29 DC	18-29 DC	200	200	200	200	200	200	200	¿?	200
Frequency [Hz] --> AC			400	400	400	400	400	400	400		360-800
Flow rate [kg/s]	0,19	0,4	3,5	1,39	3	4,4	5,2	5	8,33	13,9	3,78
at determined V (DC current):	24	23									
Delivery pressure [kPa]	206	186	165/124	200	138	82,7/210	110/193	372/193	241/344	152	48-413
Pressure at flow rate [psi]	30	27	18	29	20	16	16	28	40	22	
Pressure at flow rate [kPa]	206	186	124	200	138	110	110	193	280	152	
Current consumption [A]**	7	13	7,8	8	6,1	9,5	9	17	25	13	8,4-17
Power [W]	168	299	2185,96332	2242,013662	1709,5354	2662,3912	2522,2654	4764,279031	7006,292692	#¡VALOR!	#¡VALOR!
Motor speed [rpm]			8000		12000	12000	8000	8000	8000		5300-8500
Weight	2,92	2,34	4,2	5	4,15	6,5	7,4	6,3	8,84	10,1	7,84
Weight (regression with FFR)	3,30491	3,4244	5,1883	3,98771	4,9038	5,7004	6,1556	6,0418	7,93657	11,1059	5,34762
Error (regression with FFR)	0,38491	1,0844	0,9883	1,01229	0,7538	0,7996	1,2444	0,2582	0,90343	1,0059	2,49238
Weight (mult. regression)	4,200721164	4,18837184	5,3303982	4,744999884	5,1689124	5,6846662	6,0702307	6,4451136	8,544011748	10,50172044	4,761273768
Error (mult. regression)	1,280721164	1,84837184	1,1303982	0,255000116	1,0189124	0,8153338	1,3297693	0,1451136	0,295988252	0,40172044	3,078726232
Weight (mult. Regression 2)	3,403029491	3,468479071	5,064535102	4,069469417	4,8179093	5,5387088	5,9938047	6,104185098	8,233478757	11,05640018	4,888937481
Error (mult. Regression 2)	0,483029491	1,128479071	0,864535102	0,930530583	0,6679093	0,9612912	1,4061953	0,195814902	0,606521243	0,956400177	2,951062519
Use (main)	APU	APU	Boost	Boost	Boost	Boost	Boost	Overr/Jettison	Overr/Jettison	Overr/Jettison	Boost
Obervations	Pump + Canister* 20027	Pump + Canister 9122	20005. 9121 type improved. 8 in 747 --> feeding engines (main).	Pump + Canister 8411	Pump + Canister 8811	Pump + Canister 9107	Pump + Canister 9603	Pump + canister. 8 in 747	Pump + canister. 4 in 777	Pump + canister	Pump + Canister **var. Frequency**
Aircrafts:		B777	B747	A320	A330, A340	B777	B777-300	B747	B777		

* Canister: allows the pump to be removed without having to drain the tank.

** Current per phase



Appendix D: Electrical valves

Model:	HTE900212	12M0037	12H0068	12H0011	FRH120052K	12R0078	21-0007	21K0004	20C0003	34-0012
Entrance [in]	2	2	1	1	1,5	3	1,6	1,6		
Operating pressure [psi]	60	60	61,5	61,5		60			10	
Operating pressure [kPa]	0-414	0-414	0-424	0-424	0-414	0-414			0-69	
Proof pressure [psi]	150	120	240	240		120	30		240	36
Proof pressure [kPa]	1035	827	1654	1654	828	827	207	207	1655	248
Torque [lbf·in]	25	20	20	20		20				
at [psig]	75									
Pressure drop [kPa]			3,45	3,45	2,5					
at [kg/s]			0,987	0,987	0,5					
Torque [N·m]	2,824620833	2,25969667	2,259696667	2,259696667	0	2,259696667	0	0	0	0
Weight [kg]	1,073	0,908	0,953	0,953	0,815	2,06	0,045	0,025	0,109	0,171
Weight + actuator [kg]	1,574333333	1,40933333	1,454333333	1,454333333	0,815	2,561333333				
Flow rate [L/s]			1,05	1,05			0,88	0,88	0,26	0,051
Use (main)	LP Pedestal Valve		Engine Shut-off Valve Pedestal valve	Engine Shut-off Valve Pedestal valve	Shut-Off	Pedestal valve	Surge Tank Rib Check valve	Baffle Rib Check valve	Manifoold DRAIN for refuelling	Sump DRAIN for water
Flow	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Water
Obervations	Need a 90º actuator	Need a 90º actuator	Need a 90º actuator	Need a 90º actuator	With an actuator FRH120058K	Need a 90º actuator	Like floodgate	Like Floodgate Composite		
Aircrafts:										

Approx weight of a good reliable actuator (twin normally): 0,501333333 kg

Appendix E: Engines families. Thrust and SFC

Model	SL thrust	BPR	OPR	SL SFC	cruise SFC	Weight	Layout	cost ($M)	Entry In Service	Aircrafts
CFM56	20,600–31,200 lbf 92–139 kN	4.80-6.40	25.70-31.50	0.32–0.36 lb/lbf/h 9.1–10.2 g/kN/s	0.545–0.667 lb/lbf/h 15.4–18.9 g/kN/s	4,301–5,700 lb 1,951–2,585 kg	1+3/4LP 9HP 1HP 4/5LP	3.20-4.55	1986-1997	A320-200 A340-300
GE CF6	52,500–67,500 lbf 234–300 kN	4.66-5.31	27.1-32.4	0.32–0.35 lb/lbf/h 9.1–9.9 g/kN/s	0.562–0.623 lb/lbf/h 15.9–17.6 g/kN/s	8,496–10,726 lb 3,854–4,865 kg	1+3/4LP 14HP 2HP 4/5LP	5.9-7	1981-1987	A310-300 A330-200 DC-10-30 B747-400
JT8D	21,700 lbf 97 kN	1.77	19.2	0.519 lb/lbf/h 14.7 g/kN/s	0.737 lb/lbf/h 20.9 g/kN/s	4,515 lb 2,048 kg	1+6LP 7HP 1HP 3LP	2.99	1986	B727-200Adv B737-200
PW4000	52,000–84,000 lbf 230–370 kN	4.85-6.41	27.5-34.2	0.348–0.359 lb/lbf/h 9.9–10.2 g/kN/s		9,400–14,350 lb 4,260–6,510 kg	1+4-6LP 11HP 2HP 4-7LP	6.15-9.44	1986-1994	A310-300 B747-400
RB211	43,100–60,600 lbf 192–270 kN	4.30	25.8-33	0.563–0.607 lb/lbf/h 15.9–17.2 g/kN/s	0.570–0.598 lb/lbf/h 16.1–16.9 g/kN/s	7,264–9,670 lb 3,295–4,386 kg	1LP 6/7IP 6HP 1HP 1IP 3LP	5.3-6.8	1984-1989	B747-400
RR Trent	71,100–91,300 lbf 316–406 kN	4.89-5.74	36.84-42.7		0.557–0.565 lb/lbf/h 15.8–16.0 g/kN/s	10,550–13,133 lb 4,785–5,957 kg	1LP 8IP 6HP 1HP 1IP 4/5LP	11-11.7	1995	A330-200 A380-800
AE3007	7,150 lbf 31.8 kN		24.0	0.390 lb/lbf/h 11.0 g/kN/s		1,581 lb 717 kg				ERJ145

Appendix F: Hoses and fittings

DESIGNED FOR AIRCRAFTS - HYDRAULIC LINES								
AE246 PTFE								
Size	Operation pressure (psi)	Proof pressure (psi)	O.D. Tube Size (in)	ID (in)	OD (in)	lbs/ft	kg/m	Its weight saving construction makes it the lightest fitting available in most sizes, 40-50% lighter than previous high pressure PTFE hose.
4	3000	6000	1/4	0,212	0,385	0,108	0,161	
6	3000	6000	3/8	0,298	0,48	0,147	0,219	
8	3000	6000	1/2	0,391	0,61	0,24	0,357	
10	3000	6000	5/8	0,485	0,715	0,32	0,476	
12	3000	6000	3/4	0,602	0,888	0,509	0,757	
AE446 PTFE								AE246 with Integral Silicone Firesleeve. The AE846 is lighter than AE446 with the same fire protecting rating.
Size	Operation pressure (psi)	Proof pressure (psi)	O.D. Tube Size (in)	ID (in)	OD (in)	lbs/ft	kg/m	
4	3000	6000	1/4	0,212	0,64	0,242	0,36	
6	3000	6000	3/8	0,298	0,725	0,308	0,458	
8	3000	6000	1/2	0,391	0,865	0,44	0,655	
10	3000	6000	5/8	0,485	0,975	0,528	0,786	
12	3000	6000	3/4	0,602	1,134	0,781	1,162	
AE846 PTFE								
Size	Operation pressure (psi)	Proof pressure (psi)	O.D. Tube Size (in)	ID (in)	OD (in)	lbs/ft	kg/m	
4	3000	6000	1/4	0,212	0,581	0,198	0,295	
6	3000	6000	3/8	0,298	0,676	0,246	0,366	
8	3000	6000	1/2	0,391	0,803	0,375	0,558	
10	3000	6000	5/8	0,485	0,911	0,45	0,67	
12	3000	6000	3/4	0,602	1,086	0,679	1,01	
AE546 PTFE								AE246 Hose with Polyester Braid Chafe Guard per AS1339. Has been tested and shown to be compatible with: • Highjet Chevron • Skydrol 500B4 • JP-4 (MIL-T-5624) • AvGas Grade 100/130
Size	Operation pressure (psi)	Proof pressure (psi)	O.D. Tube Size (in)	ID (in)	OD (in)	lbs/ft	kg/m	
4	3000	6000	1/4	0,212	0,49	0,137	0,204	
6	3000	6000	3/8	0,298	0,57	0,187	0,278	
8	3000	6000	1/2	0,391	0,68	0,308	0,458	
10	3000	6000	5/8	0,485	0,8	0,374	0,557	
12	3000	6000	3/4	0,602	0,965	0,605	0,9	

"Super C" Fittings - Weight (lbs)							
1-Flared straight	2-Flared 45º	3-Flared 90º	1-Flareless straight	2-Flareless 45º	3-Flareless 90º	Average (lbs)	**AVG (kg)**
0,057	0,065	0,065	0,06	0,068	0,068	0,0638333	0,029
0,077	0,1	0,1	0,083	0,106	0,106	0,0953333	0,043
0,143	0,19	0,19	0,154	0,2	0,2	0,1795	0,081
0,209	0,284	0,284	0,227	0,302	0,302	0,268	0,122
0,263	0,39	0,39	0,31	0,42	0,429	0,367	0,166

"Super gem" Fittings - Weight (lbs)							
1-Flared straight	2-Flared 45º	3-Flared 90º	1-Flareless straight	2-Flareless 45º	3-Flareless 90º	Average (lbs)	**AVG (kg)**
0,097	0,127	0,127	0,098	0,13	0,13	0,1181667	0,054
0,142	0,196	0,196	0,146	0,2	0,2	0,18	0,082
0,222	0,314	0,314	0,234	0,323	0,323	0,2883333	0,131
0,333	0,442	0,442	0,347	0,454	0,454	0,412	0,187
0,574	0,748	0,748	0,61	0,768	0,768	0,7026667	0,319

I think that the difference between both is that the first ones are permanent fittings (integral hose subministrated) while the second ones are reusable. The WEIGHT it's more or less the double.

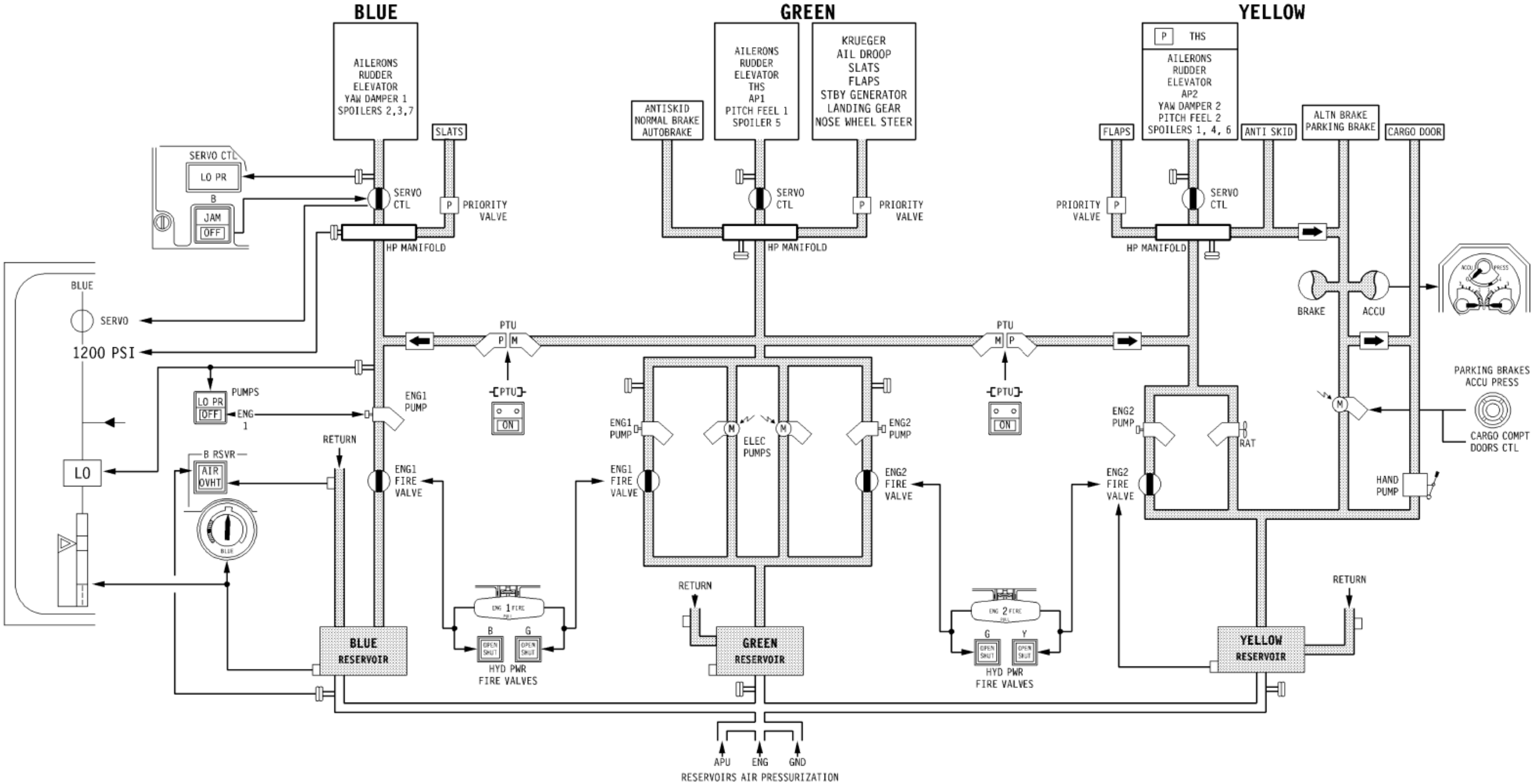
DESIGNED FOR FUEL LINES					
AE645-PTFE BRAID					
Size	Operation pressure (psi)	ID (in)	OD (in)	lbs/ft	kg/m
4	300	0,27	0,482	0,07	0,1
6	300	0,345	0,575	0,08	0,12
8	250	0,51	0,76	0,13	0,19
10	250	0,6	0,87	0,15	0,22
12	200	0,79	1,075	0,2	0,3
16	200	0,982	1,315	0,26	0,39
AE641-CRES BRAID					
4	300	0,27	0,482	0,1	0,15
6	300	0,345	0,575	0,1	0,15
8	250	0,51	0,76	0,15	0,22
10	250	0,6	0,87	0,2	0,3
12	200	0,79	1,075	0,31	0,46
16	200	0,982	1,315	0,39	0,58

Sleeves - Weight (lbs)						
AE102/624-silicone coated	AE251 - Polyolefin	AE208 - Nylon	AE506 - Teflon	AE138 - Neoprene	Average (lbs/ft)	**AVG (kg/m)**
0,0093	0,0018	0,0007	0,0017	0,002	0,0031	0,005
0,0131	0,0018	0,0007	0,0019	0,0029	0,00408	0,006
0,0145	0,0028	0,002	0,0024	0,0039	0,00512	0,008
0,0155	0,0028	0,002	0,0028	0,0046	0,00554	0,008
0,02	0,0046	0,002	0,0037	0,0072	0,0075	0,011

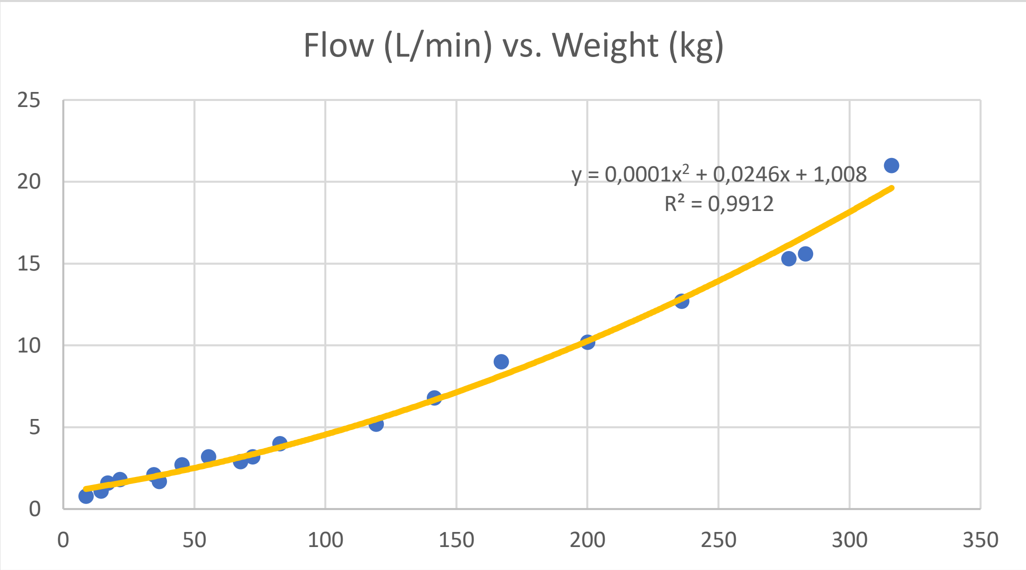
Appendix G: Inputs of the fuel program

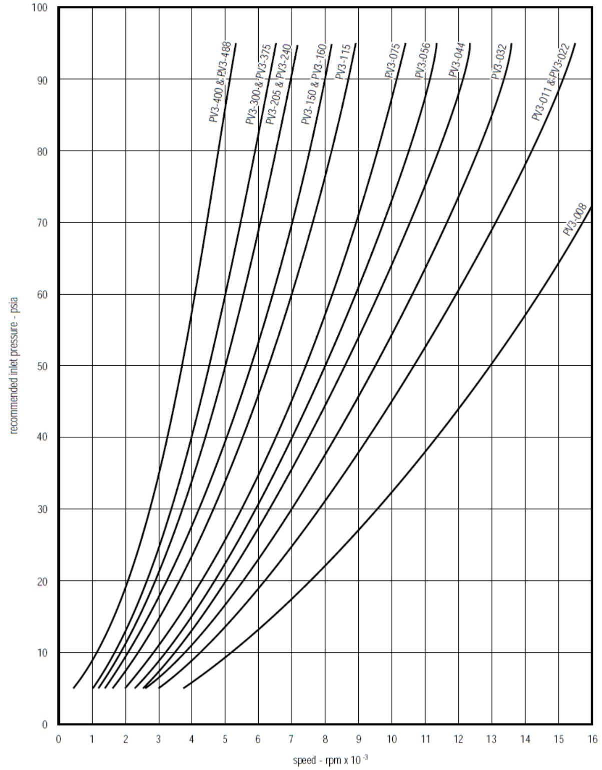
Variable	Units	Description
PARAMETERS		
fd	kg/L	Fuel density
v	mm^2/s=cSt	Fuel kinematic viscosity
u	Pa·s =	Fuel dynamic viscosity - Optional
sg_s	-	Specific gravity of the sealant (once cured)
cord_a	cm^2	Area of the sealant weld
GEOMETRY		
L	m	Length of the aircraft
D_f	m	Diameter of the fuselage; width
tail_x	m	Tail position (explained in code)
AR	-	Aspect ratio
b	m	Span
tr	-	Taper ratio
t	%	Thickness to chord average
sweep	º	¼ chord sweep angle
f_spar	%	Position of the front spar respect to leading edge
r_spar	%	Position of the rear spar respect to leading edge
n_spars	-	number of middle spars (extra of the main) - Optional
ribs_dw	m	Distance between ribs
cranked_wing	Yes/No	Whether it has cranked wing or trapezoidal wing
AR_ht	-	Aspect ratio of the horizontal tail
b_ht	m	Span of the horizontal tail
tr_ht	-	Taper ratio of the horizontal tail
sweep_ht	º	¼ horizontal tail chord sweep
ENGINES		
spanwise_loc	%	Position of the engines in wings
other_eng	m	Position of the engines in tail
mf	kg/s	Fuel flow rate per engine
p_mf	kPa	Pressure at flow rate - Optional
APU		
APU_x	m	Longitudinal distance from wing root chord to APU
APU_shared	Yes/No	Independent feeding or shared with trim tank
FUEL LAYOUT		
in_feed	Yes/No	If each engine has a feed line or is shared in each wing
Tanks	0/1/v	Number and type of tanks under one wing
CT	Yes/No	Whether it has Center Tank or not
TrimT	Yes/No	Whether it has Trim Tank or not
ett	Unitary	Where the tank on tail finishes
n_gal	1/2	Number of transfer galleries
aux_pumps	-	Number of auxiliary boost pumps
suction_feed	Yes/No	Whether the feeding pumps have suction valves - Optional
defuel_con	1/2	Whether the feed gallery joins the transfer gallery with 1 or 2 valves
jett	Yes/No	Whether it has jettison function
jett_loc	mid/tip	Location of the jettison ejectors
D_p	inches	Diameter of the fuel pipes

Appendix H: Hydraulic system of the A310



Appendix I: EDP (Hydraulic system)





Pump Size	Recommended speed (rpm)		Maximum Displacement		Theo. Flow at normal speed		Dry Weight		Qoutlet	Theore. Torque	Tinput	Shaft input Power	Hydraulic output Power	Power loss
	Normal	Maximum	in^3/rev	mL/rev	gpm	L/min	lbs	kg	L/min	N*m	N*m	W	W	W
PV3- 003	18000	22500	0,03	0,5	2,33766234	9	1,7	0,8	8,64	1,647253661	1,79049311	3375	2980,8	394,2
PV3- 006	15000	18750	0,061	1	3,96103896	15	2,4	1,1	14,4	3,294507322	3,58098622	5625	4968	657
PV3- 008	13500	16800	0,08	1,31	4,67532468	17,685	3,4	1,6	16,9776	4,315804592	4,691091948	6631,875	5857,272	774,603
PV3- 011	12500	15600	0,11	1,803	5,95238095	22,5375	3,7	1,8	21,636	5,939996702	6,456518154	8451,5625	7464,42	987,1425
PV3- 019	12100	15100	0,192	3,15	10,0571429	38,115	3,7	1,7	36,5904	10,37769806	11,28010659	14293,125	12623,688	1669,437
PV3- 022	10000	12500	0,22	3,605	9,52380952	36,05	4,6	2,1	34,608	11,8766989	12,90945532	13518,75	11939,76	1578,99
PV3- 032	9000	11250	0,32	5,244	12,4675325	47,196	6	2,7	45,30816	17,2763964	18,77869174	17698,5	15631,3152	2067,1848
PV3- 044	8000	10000	0,44	7,21	15,2380952	57,68	7,1	3,2	55,3728	23,75339779	25,81891064	21630	19103,616	2526,384
PV3- 049	8800	11000	0,488	8	18,5904762	70,4	6,4	2,9	67,584	26,35605858	28,64788976	26400	23316,48	3083,52
PV3- 056	8200	10250	0,56	9,177	19,8787879	75,2514	7,1	3,2	72,241344	30,23369369	32,86271054	28219,275	24923,26368	3296,01132
PV3- 075	7000	8750	0,75	12,29	22,7272727	86,03	8,9	4	82,5888	40,48949499	44,01032064	32261,25	28493,136	3768,114
PV3- 115	6600	8250	1,15	18,85	32,8571429	124,41	11,5	5,2	119,4336	62,10146302	67,50159024	46653,75	41204,592	5449,158
PV3- 150	6000	7500	1,5	24,58	38,961039	147,48	15	6,8	141,5808	80,97898997	88,02064128	55305	48845,376	6459,624
PV3- 205	5900	7400	1,8	29,5	45,974026	174,05	19,8	9	167,088	97,187966	105,6390935	65268,75	57645,36	7623,39
PV3- 240	5300	6600	2,4	39,33	55,0649351	208,449	22,5	10,2	200,11104	129,572973	140,840188	78168,375	69038,3088	9130,0662
PV3- 300	5000	6250	3	49,16	64,9350649	245,8	28	12,7	235,968	161,9579799	176,0412826	92175	81408,96	10766,04
PV3- 375	4800	6000	3,75	61,45	77,9220779	294,96	34,5	15,6	283,1616	202,4474749	220,0516032	110610	97690,752	12919,248
PV3- 400	4400	5500	4	65,55	76,1904762	288,42	33,5	15,3	276,8832	215,954955	234,7336467	108157,5	95524,704	12632,796
PV3- 488	4100	5125	4,9	80,3	86,969697	329,23	46,3	21	316,0608	264,548938	287,5531934	123461,25	109040,976	14420,274

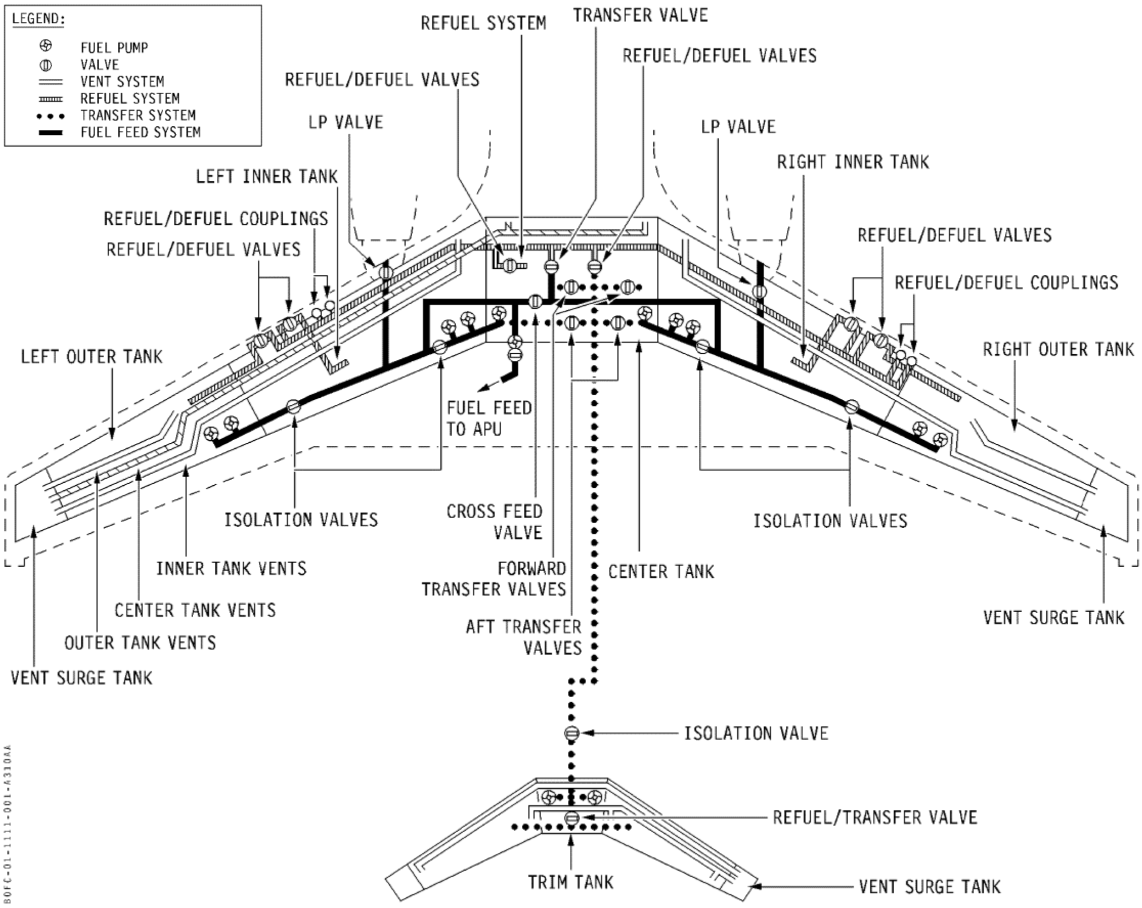
Appendix J: Hydraulic functions classification

Component	Criticality	Systems (n/3)	Observations
Nose wheel steering	Low	1*	*New Airbus have this subsystem controlled by both main systems.
Landing gear	Medium	1	Manual free fall
Flaps	High	2	Flaps&Slats in system 1, then Flaps in system 2 and Slats in system 3.
Slats	High	2	
Reverser engine X	Medium	1	Each system (X) with EDP one engine.
Normal brakes	Medium	1	
Yaw damper X	Low	1	Each system (X) with EDP one engine.
Rudder	Very high	3	The only surface control that works individually.
Stabilizer	Medium	2	
Elevator	High	2 or 3	Divided with L/R parts.
Ailerons	High	2 or 3	Divided with L/R parts.
Spoilers	Low	1	The total spoiler surface is divided in small parts --> Less criticality. Each system controls only a number of the L&R parts.
Alternate/Park. Brake	Low	1	The other system (regarding the one that controls the normal brakes)
Emergency generator	Low	1	Controlled by the "alternative" system, which normally is electrically driven.
Wing tip brakes (slats/flaps; L/R)	Medium	2	Are safety devices to avoid any undue movements in case of failure.
Cargo doors	Low	1	Normally in the "alternative" system and also the aircrafts have a hand pump (connected to this system) for this function in ground.
Back-up Yaw damper unit	Low	1 or 2	
Pitch Trim X	Low	1	
Ail droop	Medium	1	
Antiskid (ABS)	Low-medium	1 or 2	

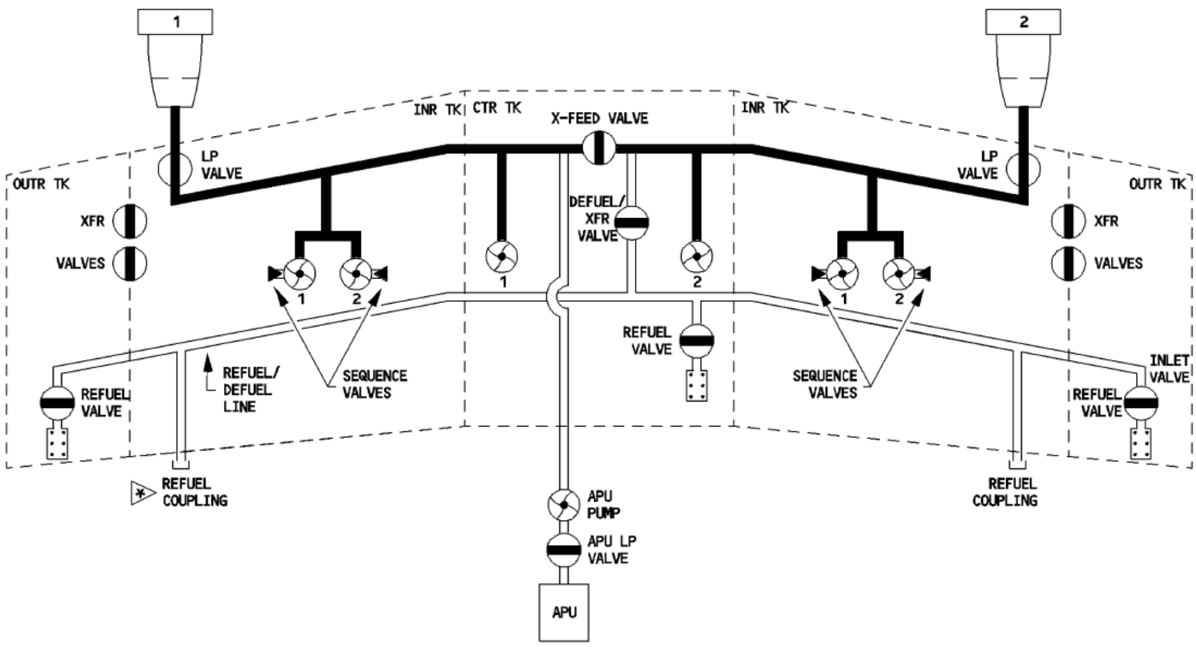
Remember: if we have PTU (pressurization) between the 2 "main" systems we have an extra redundancy.

Yellow: we can estimate the power required.

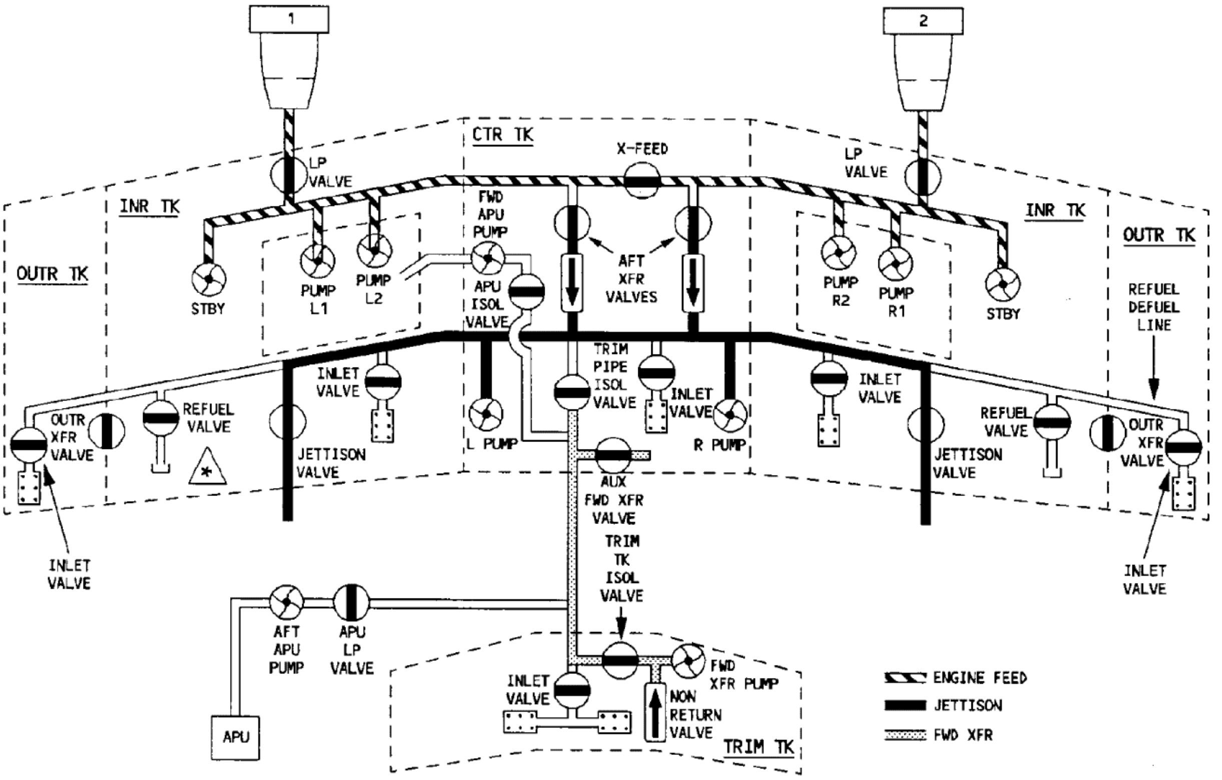
Appendix K: Aircraft layouts



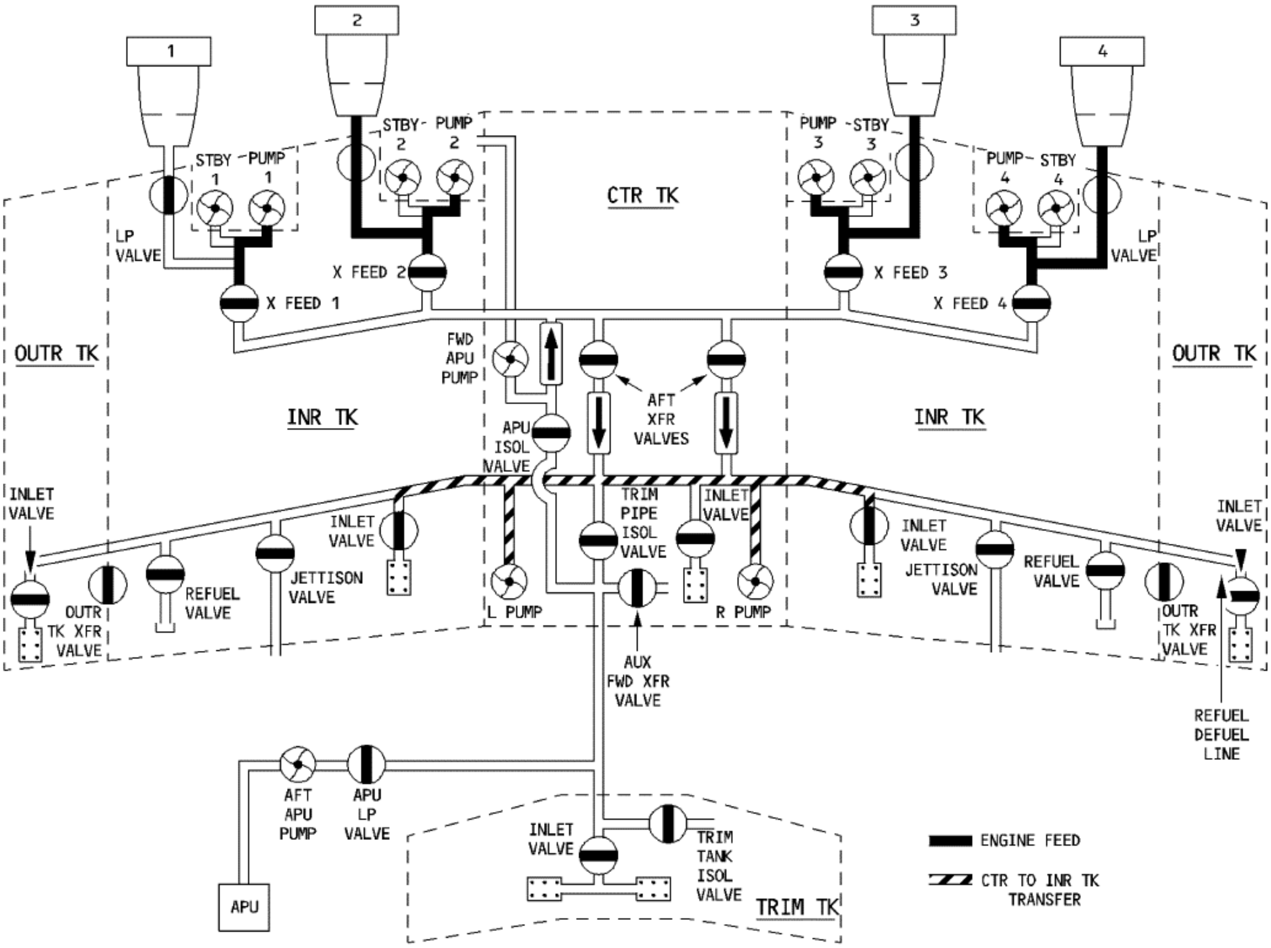
Airbus A310



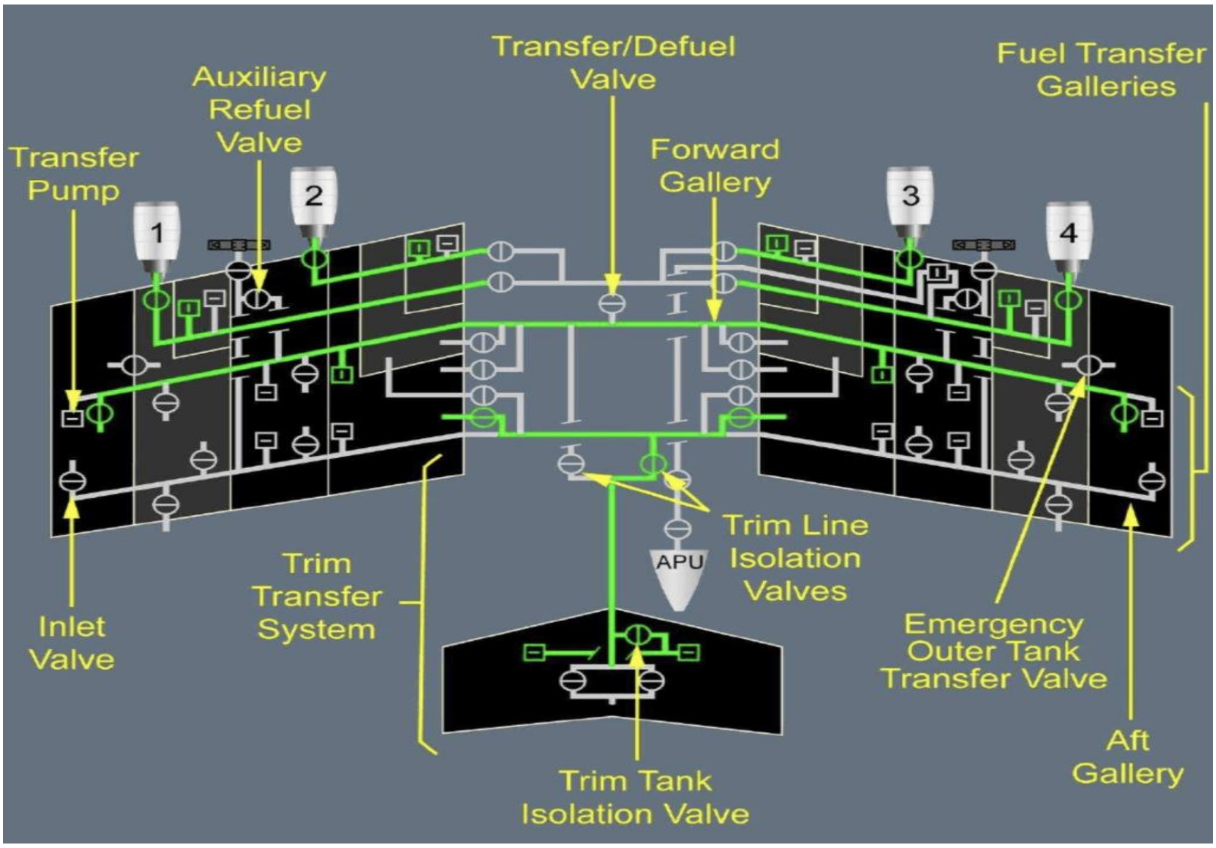
Airbus A320



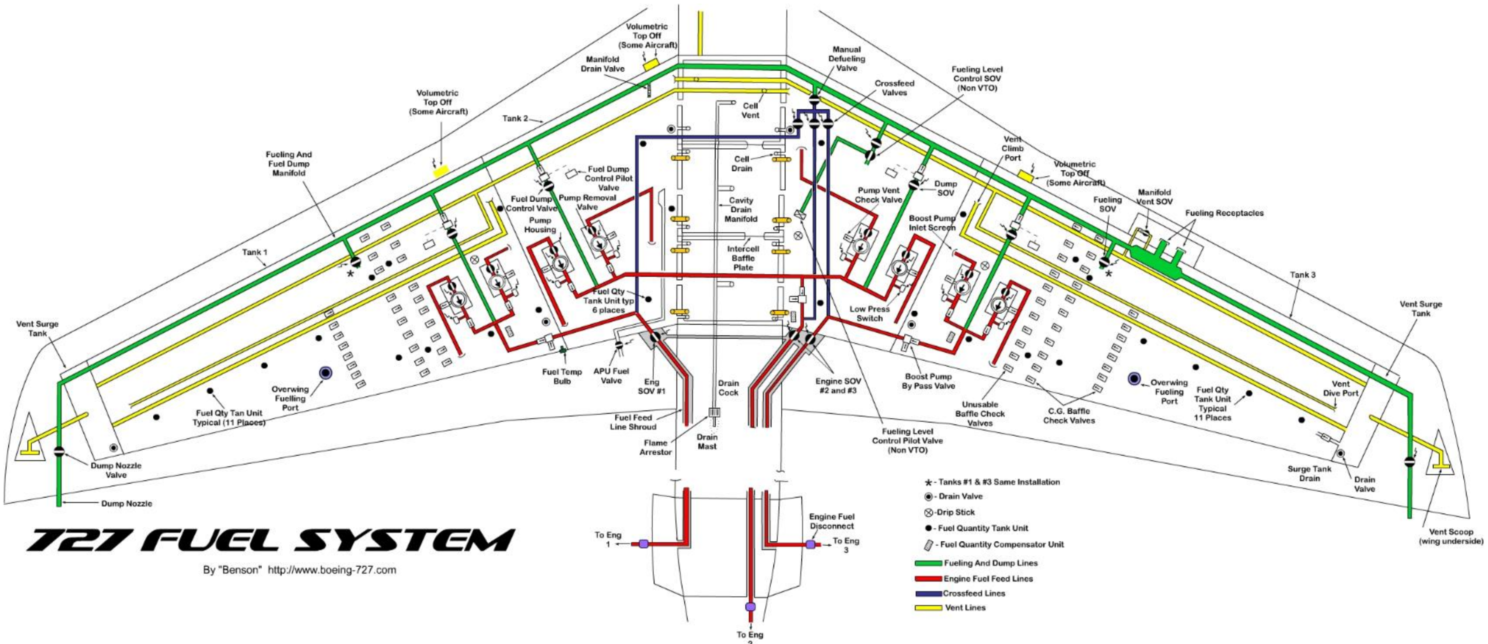
Airbus A330



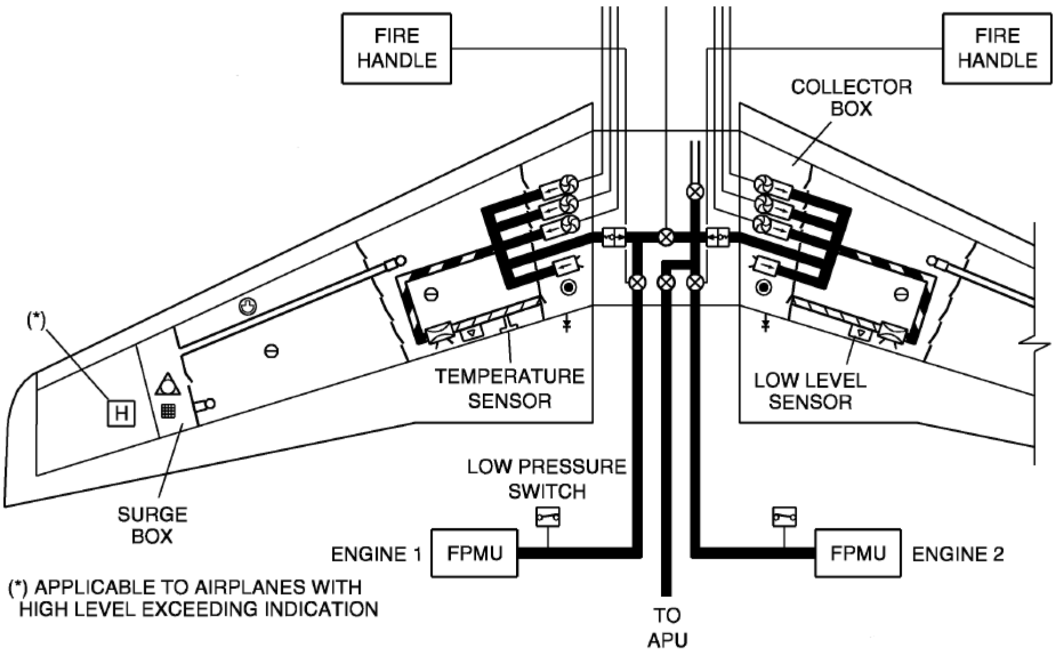
Airbus A340



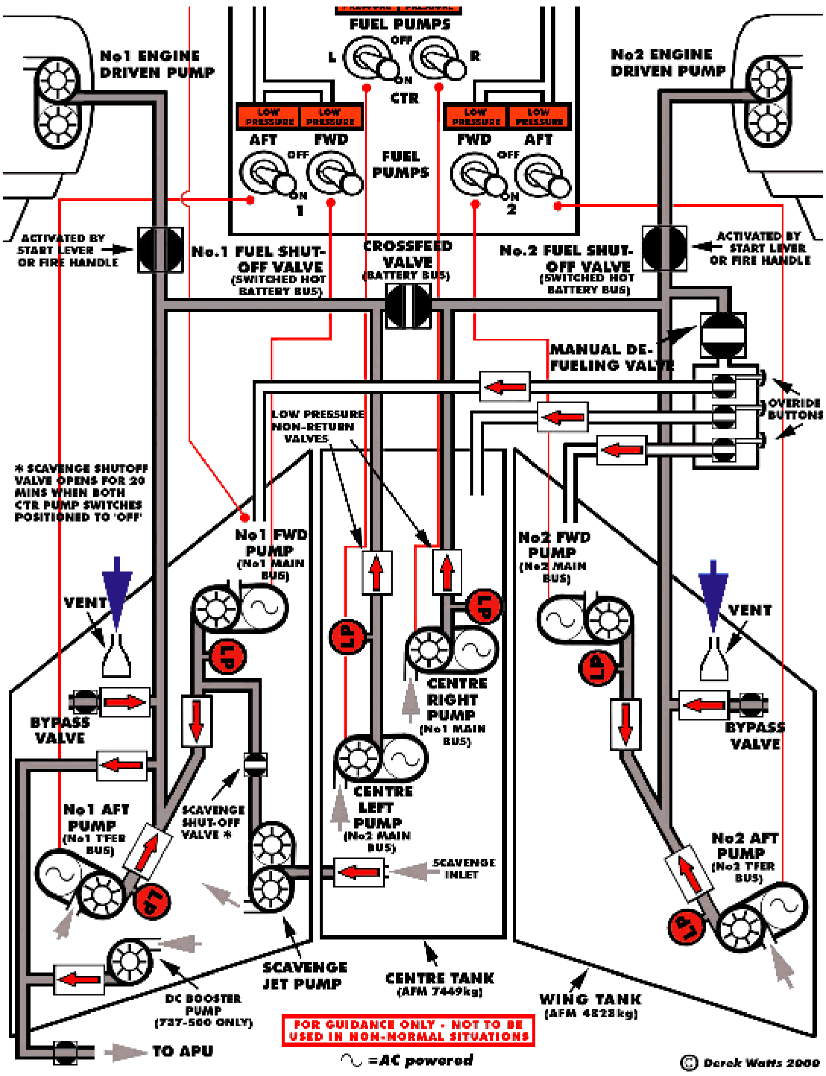
Airbus A380



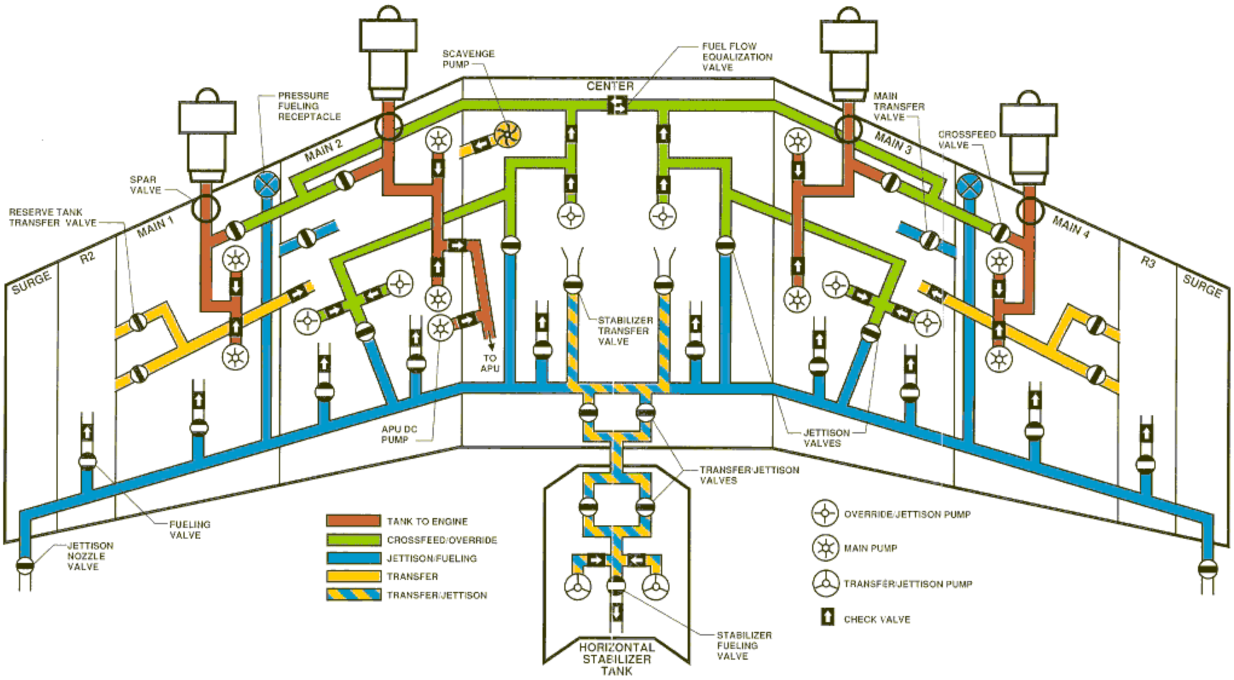
Boeing 727



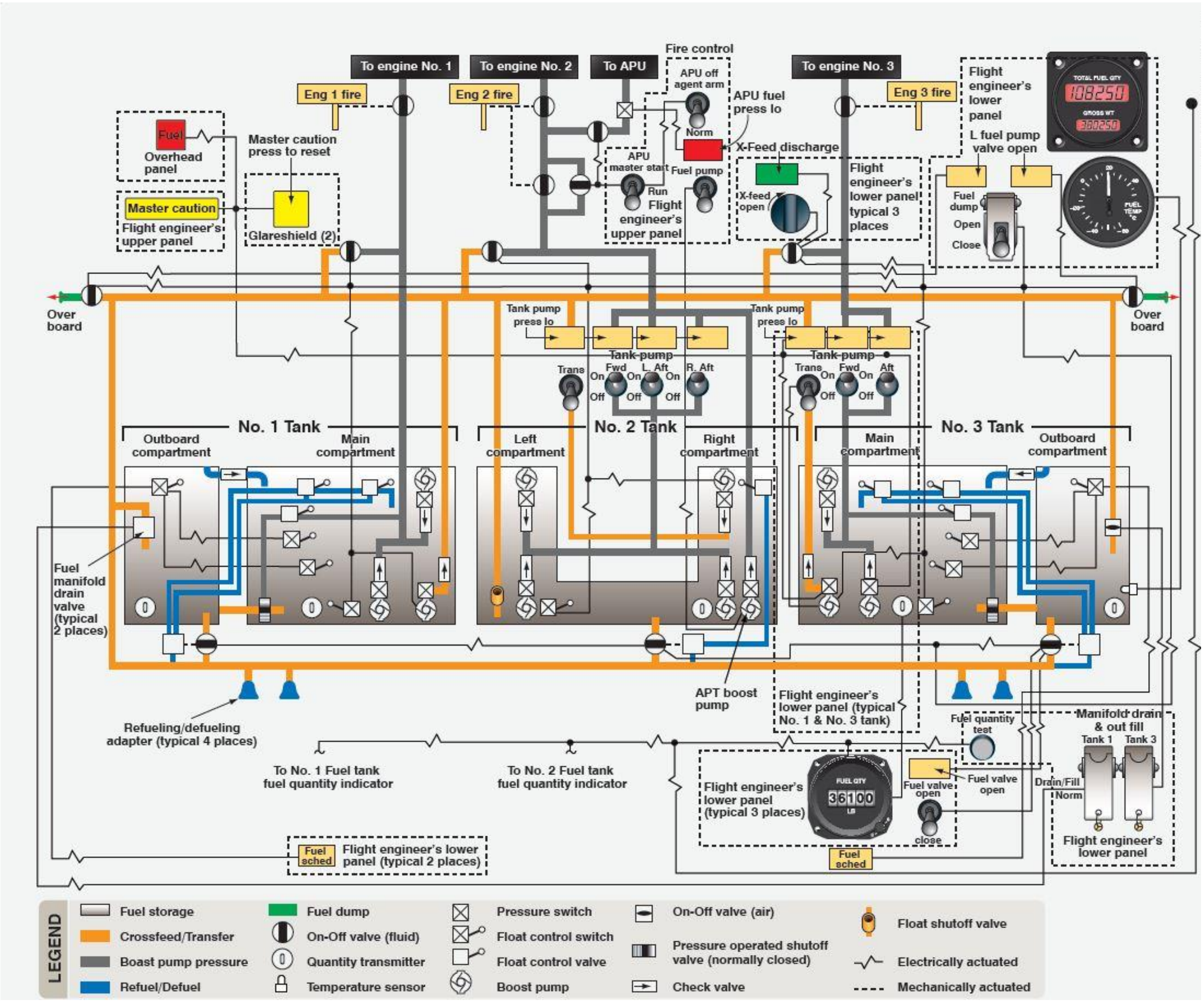
Embraer ERJ145



Boeing 737

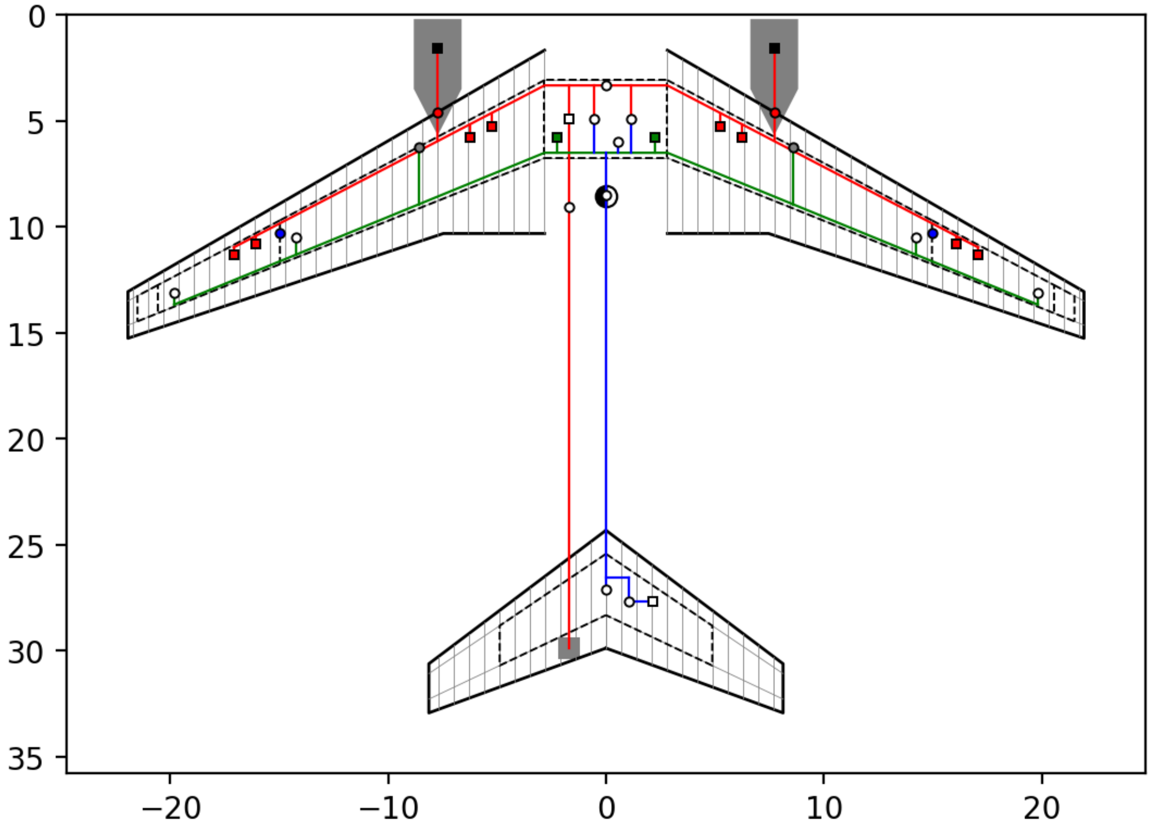


Boeing 747

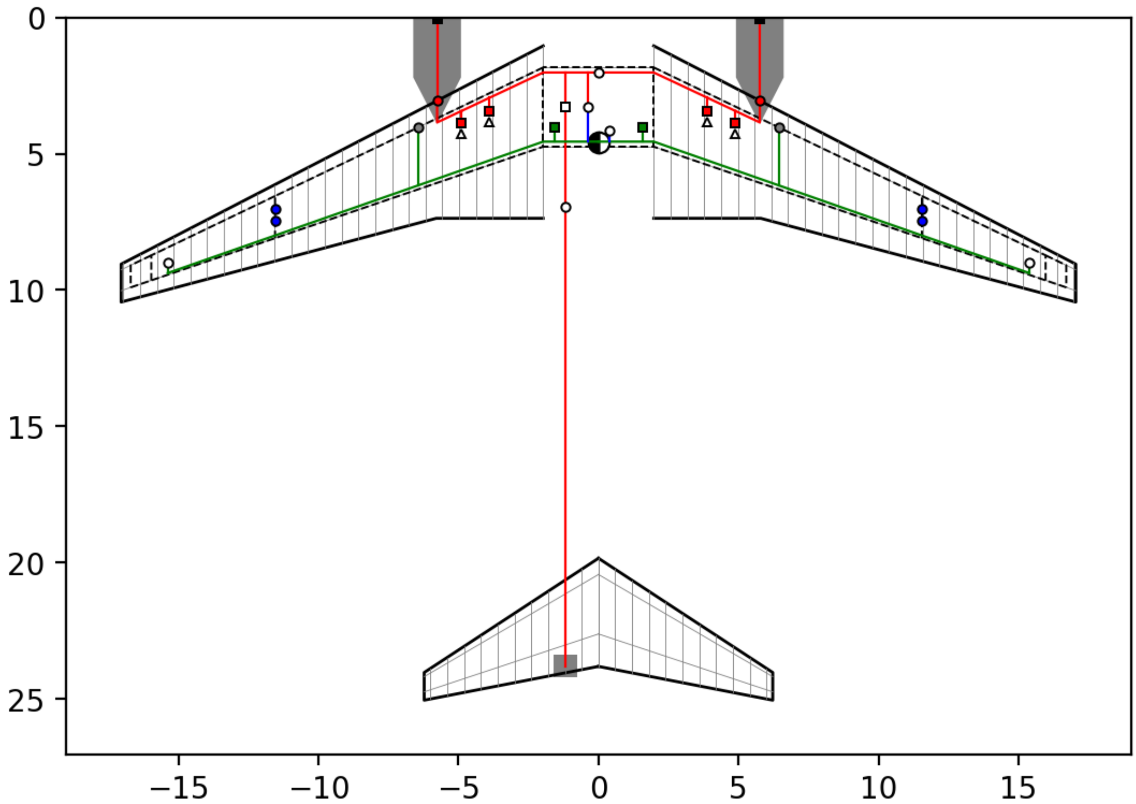


McDonnell Douglas DC-10-40

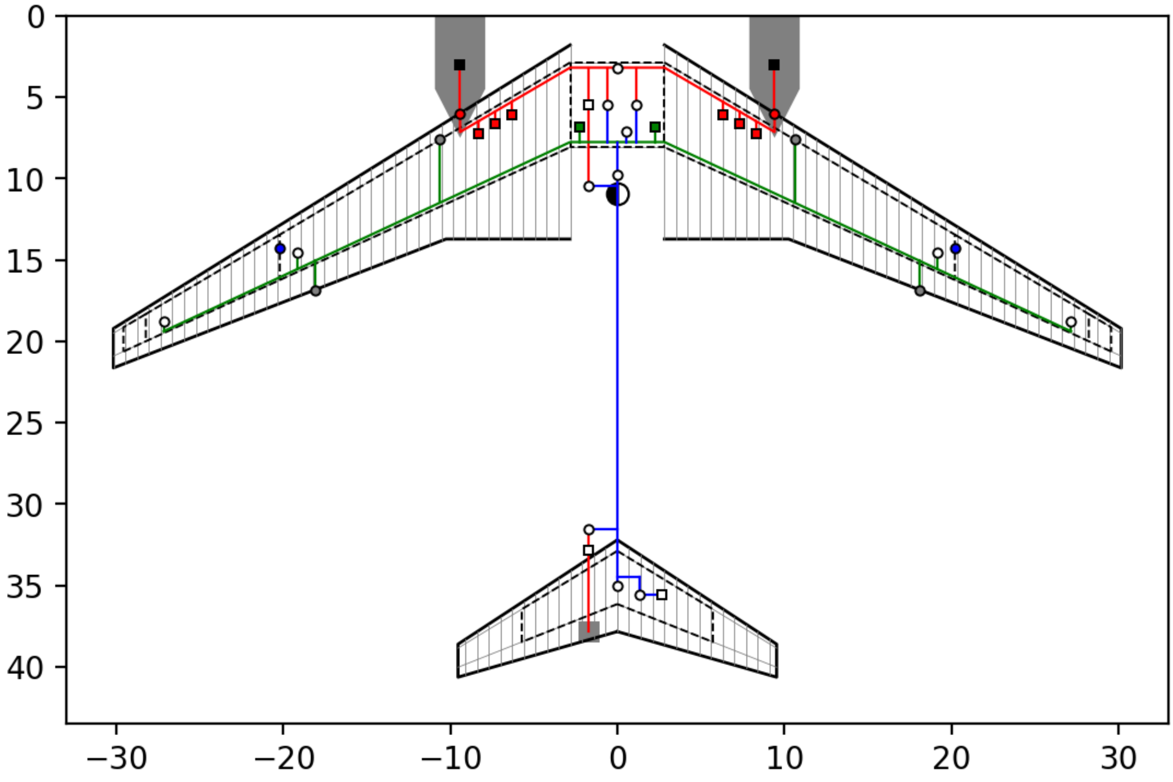
Appendix L: Layouts estimated by the program



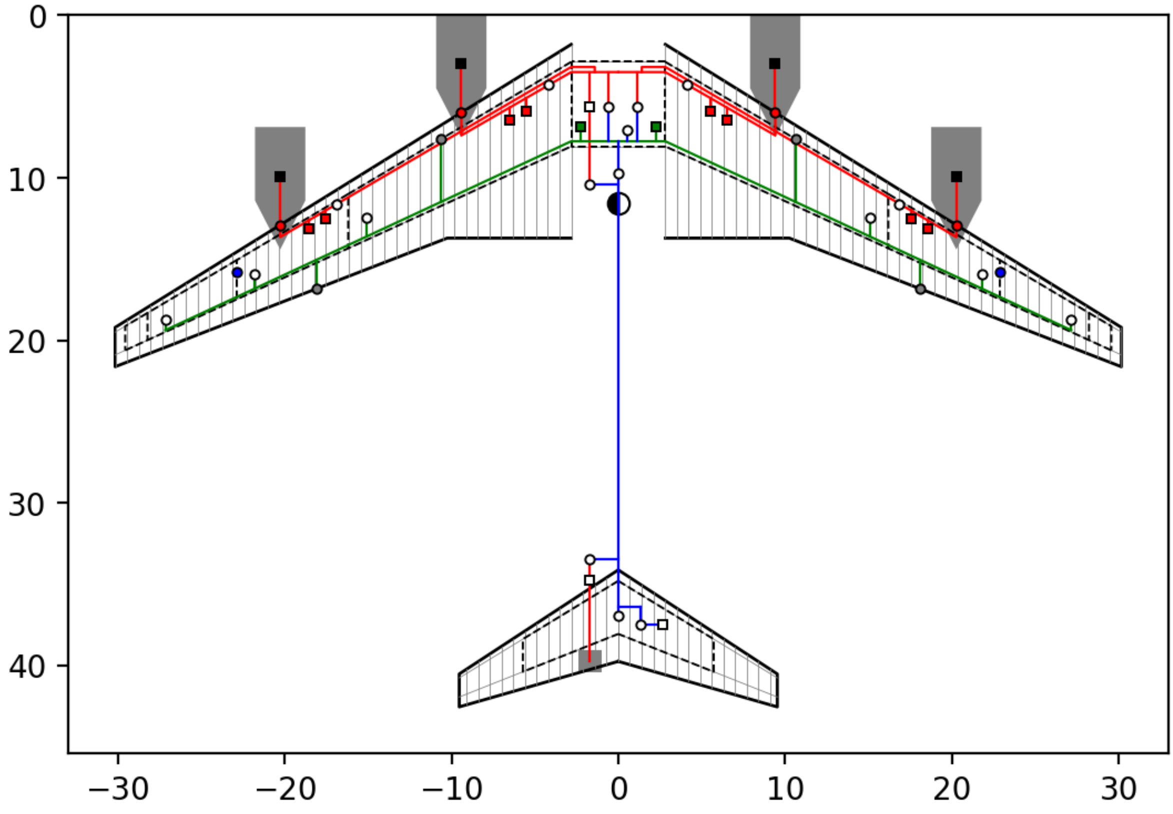
Airbus A310-300



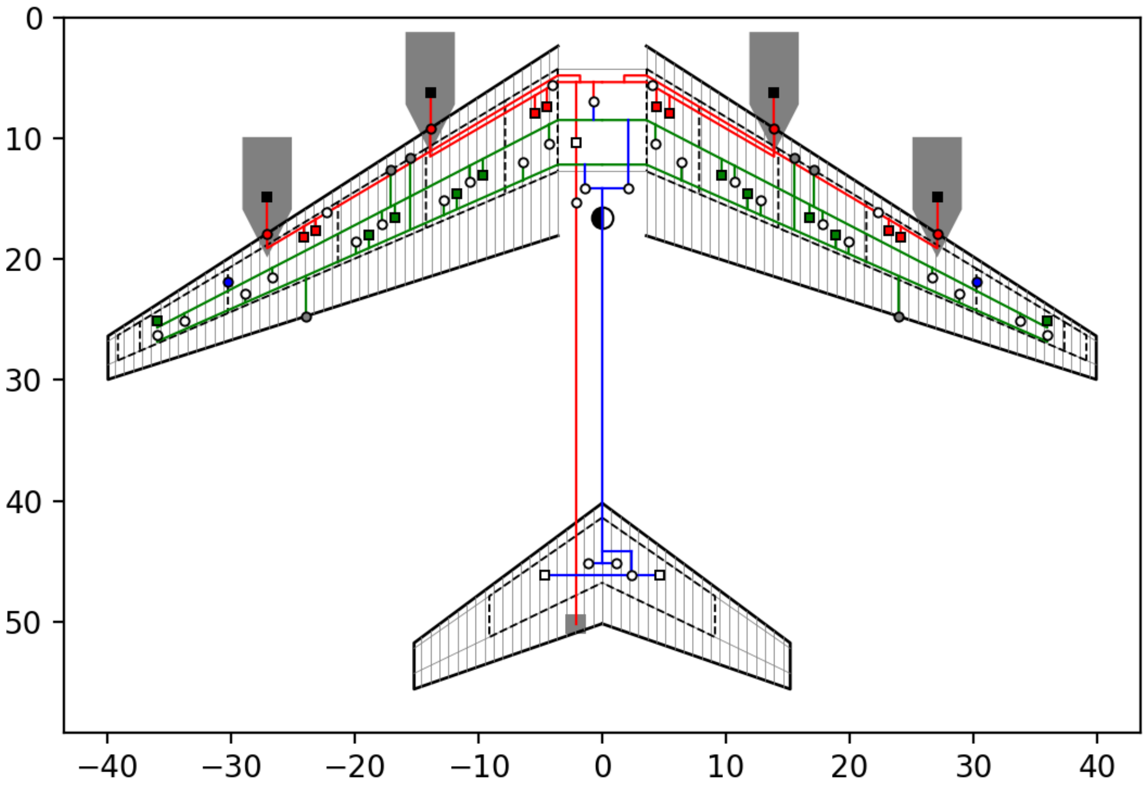
Airbus A320-200



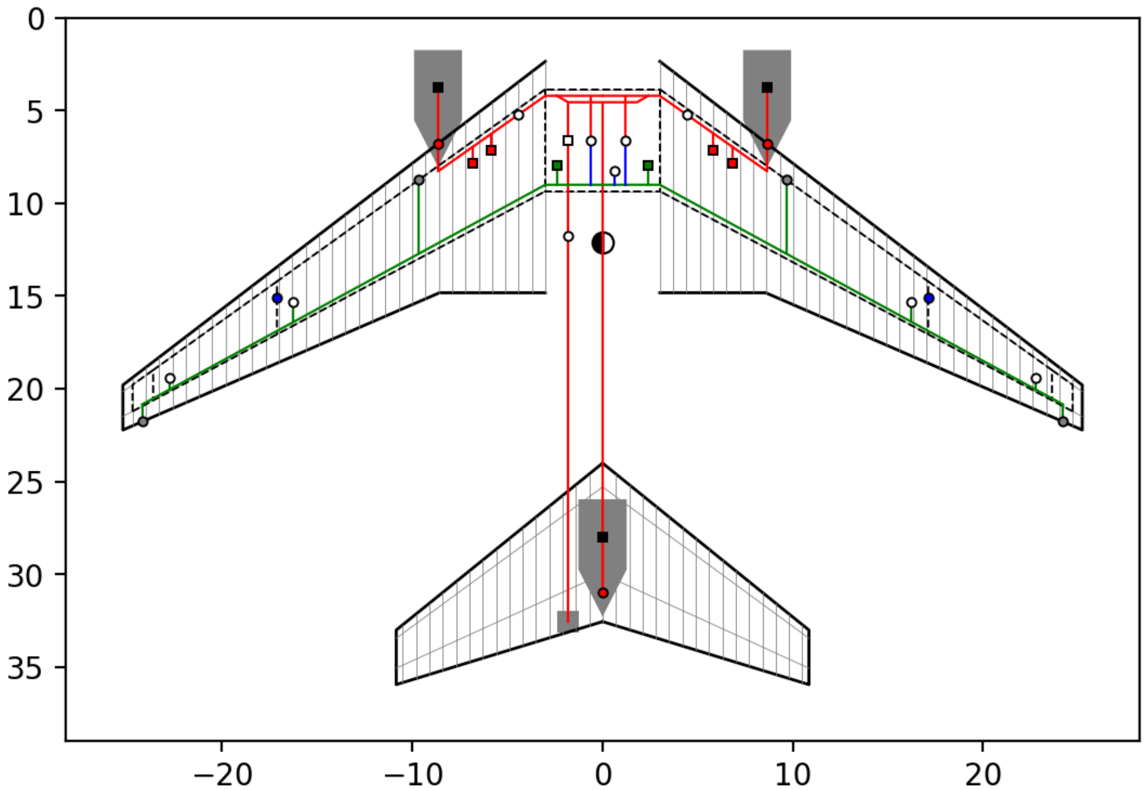
Airbus A330-200



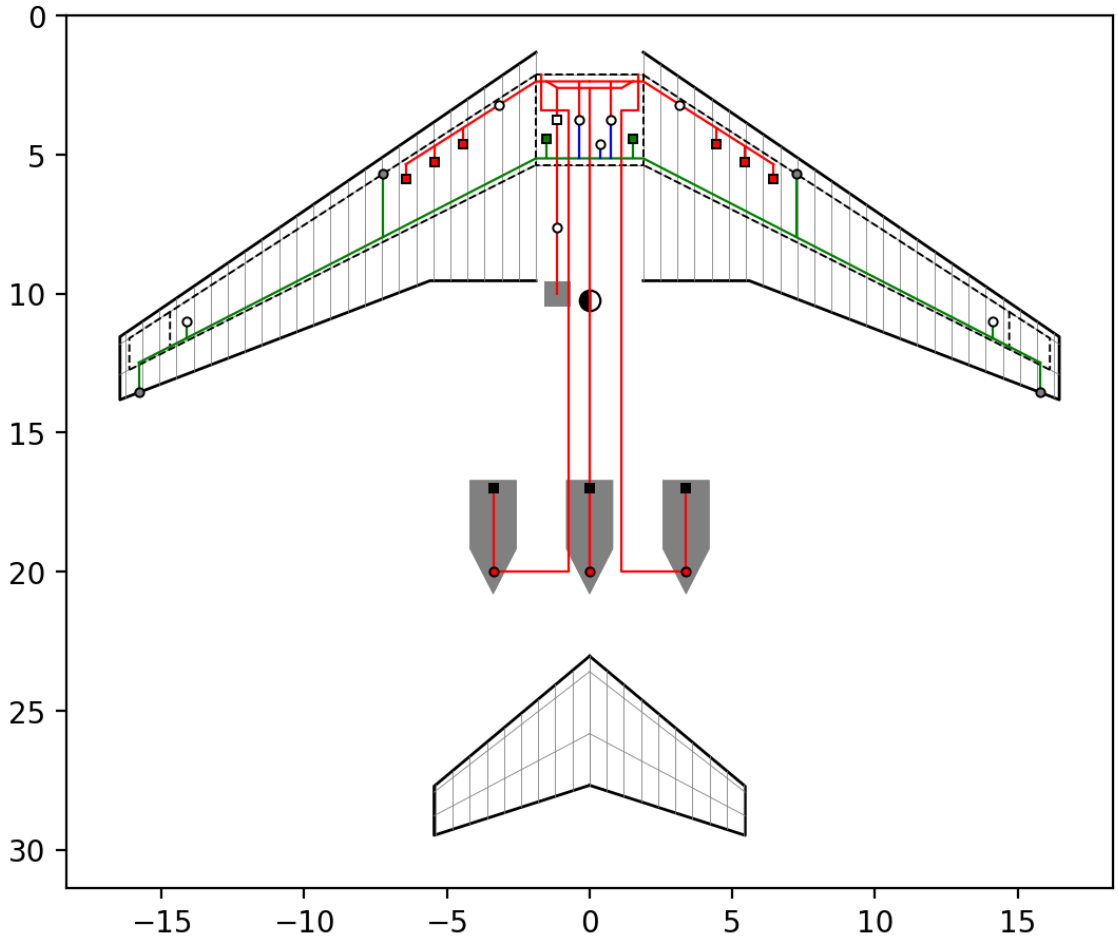
Airbus A340-300



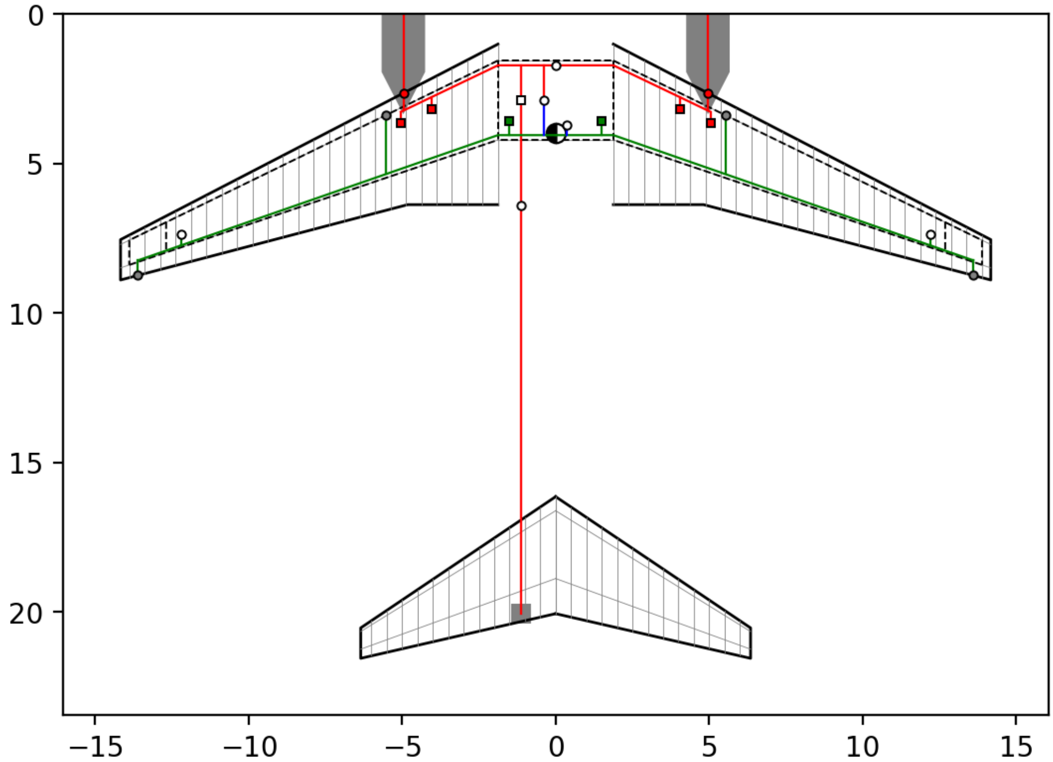
Airbus A380-800



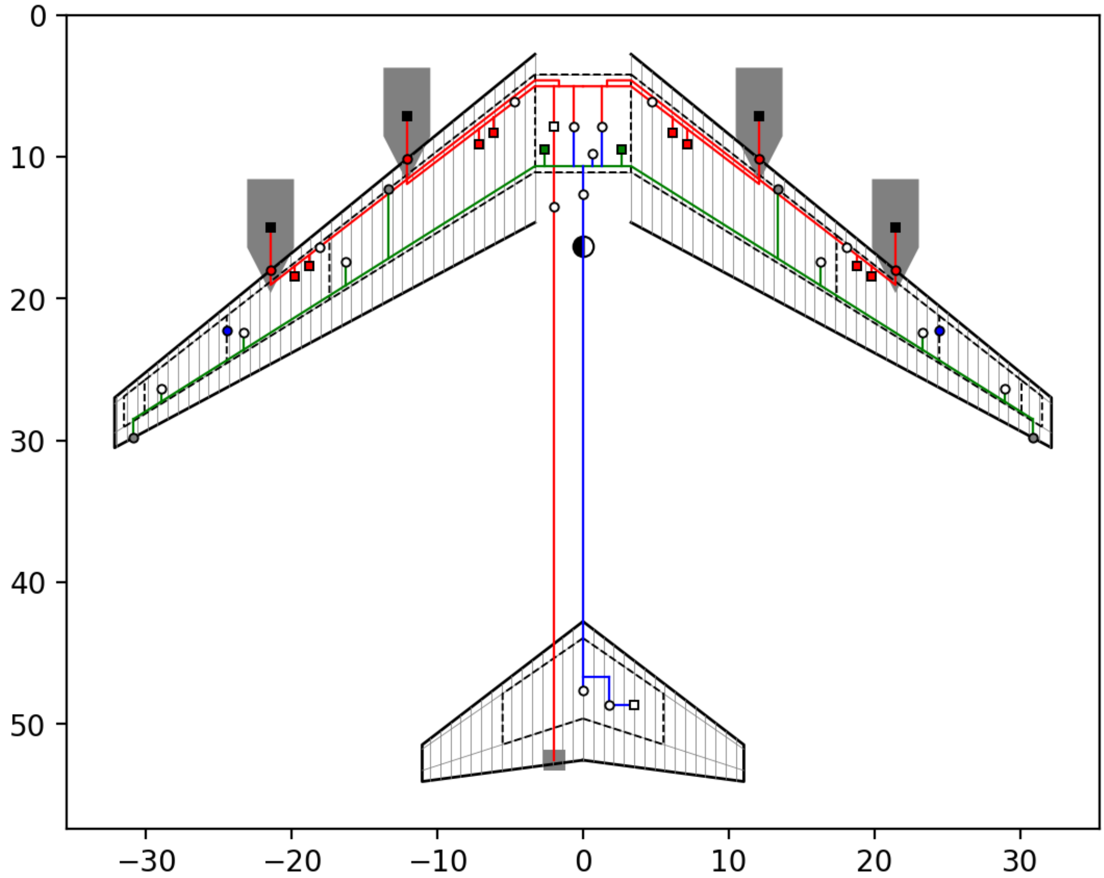
McDonnell Douglas DC-10-40



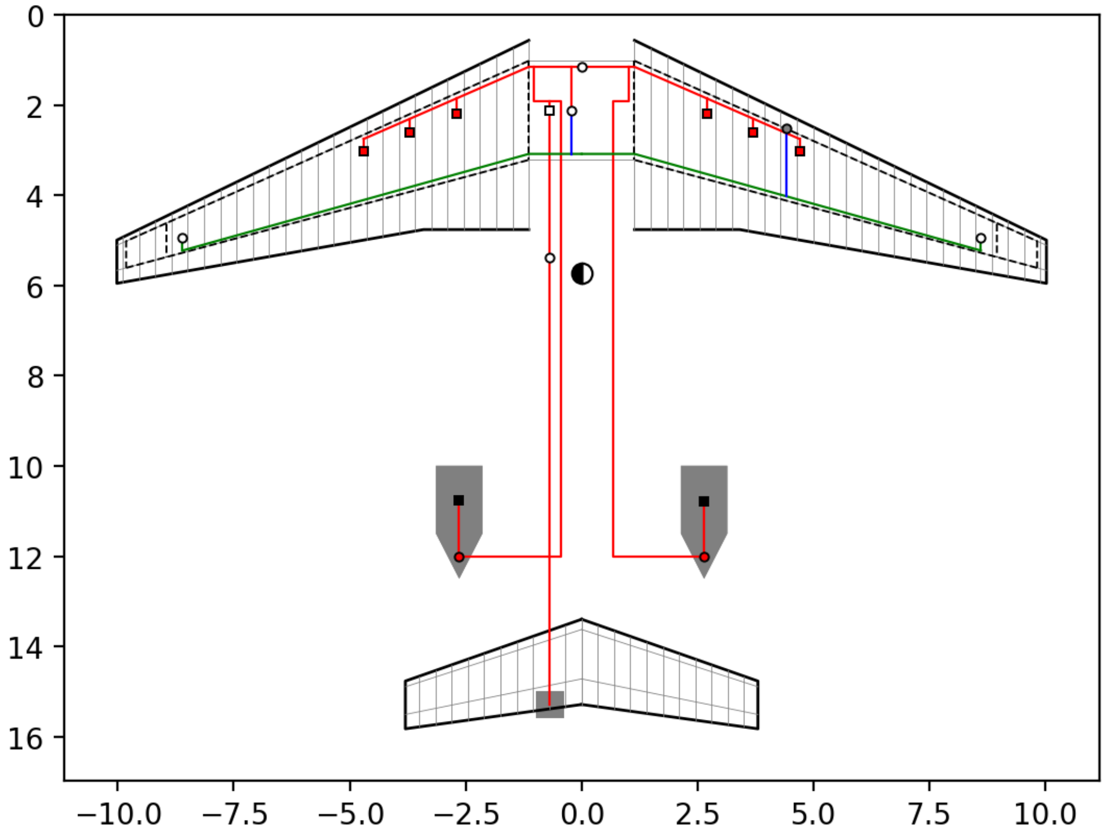
Boeing 727-200 Advanced



Boeing 737-200



Boeing 747-400



Embraer ERJ145